NDE/Imaging Technologies for Structural and Infrastructure Condition Assessment

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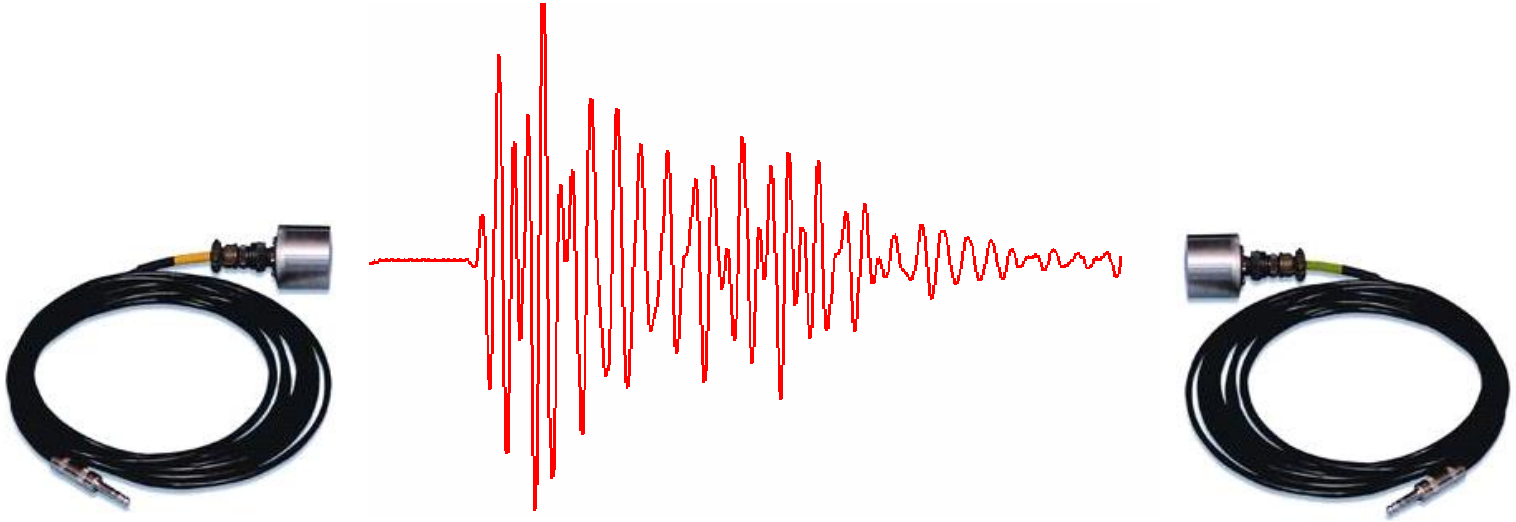
Presentation Outline

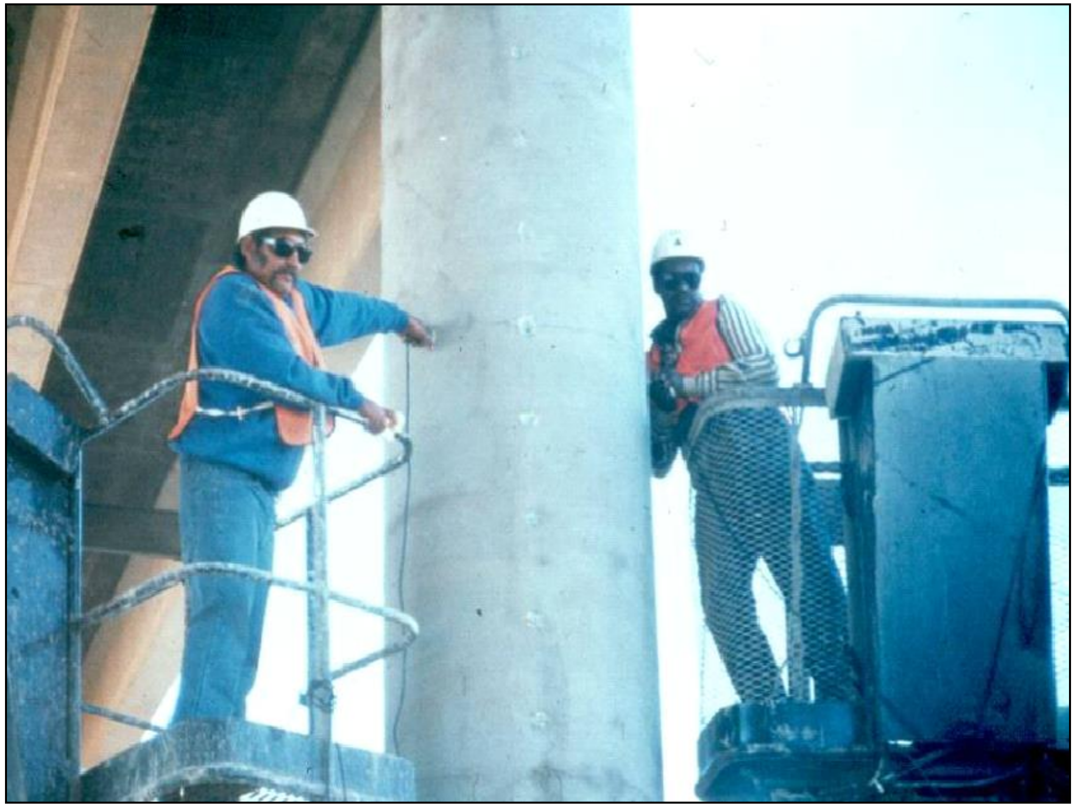
- **Ultrasonic Pulse Velocity and Tomography for Concrete Integrity and Strength**
- **Corrosion Mitigation for Post-Tensioned Ducts by Grout/Void Detection**
  - Impact Echo Scanning
- **Corrosion Detection in Bridge and Parking Decks**
  - Bridge Deck Scanner with Impact Echo
  - Acoustic Sounding Comparisons
  - Ground Penetrating Radar
  - Asphalt Overlaid Deck Delamination mapping with Surface Waves
- **Impact Echo testing of a stone door in the Great Pyramid in Giza Egypt**
- **Slab Impulse Response and Ground Penetrating Radar for Void Detection below Slabs**

Ultrasonic/Sonic Pulse Velocity Tests



Applications

- ASTM Standard C597
- Used to locate voids, honeycomb, cracks, discontinuities or poor quality concrete
- Best used on structures with 2 accessible sides
  - Beams
  - Columns
  - Elevated Slabs
- Sonic Pulse Velocity (SPV)Used on large structures

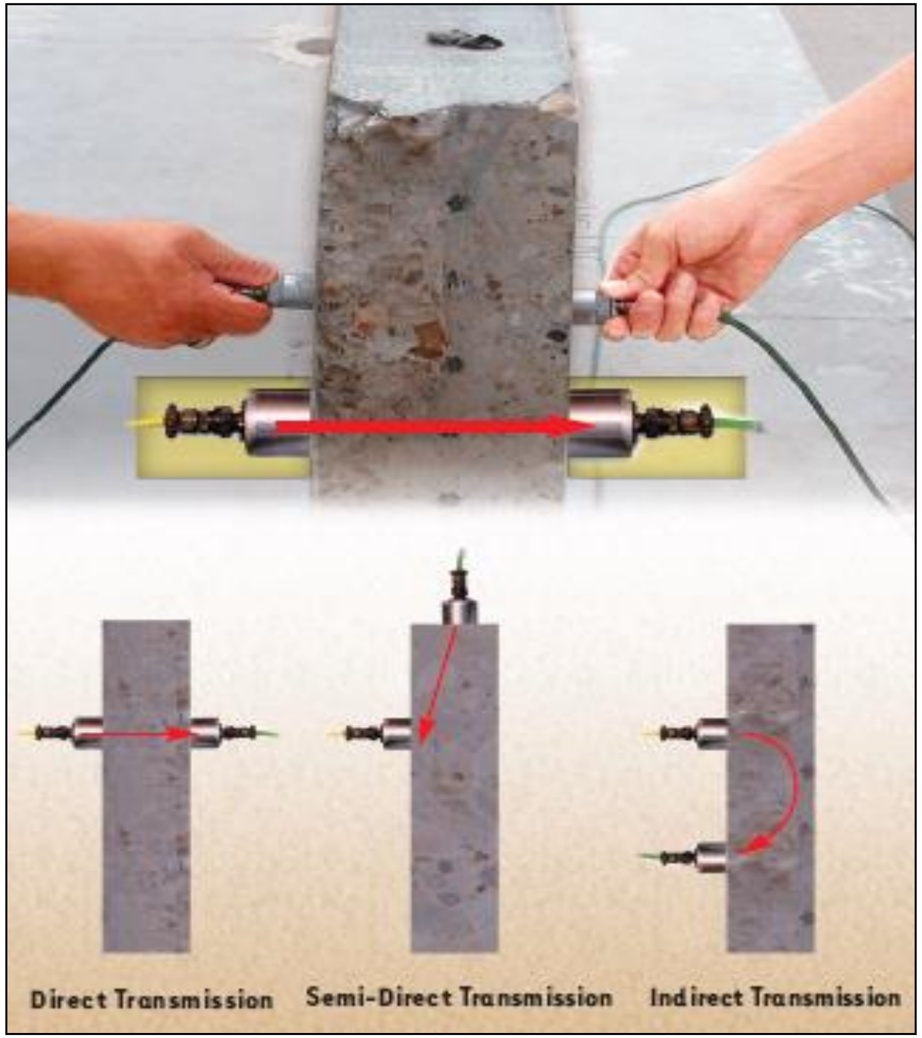


UPV Testing on a Column

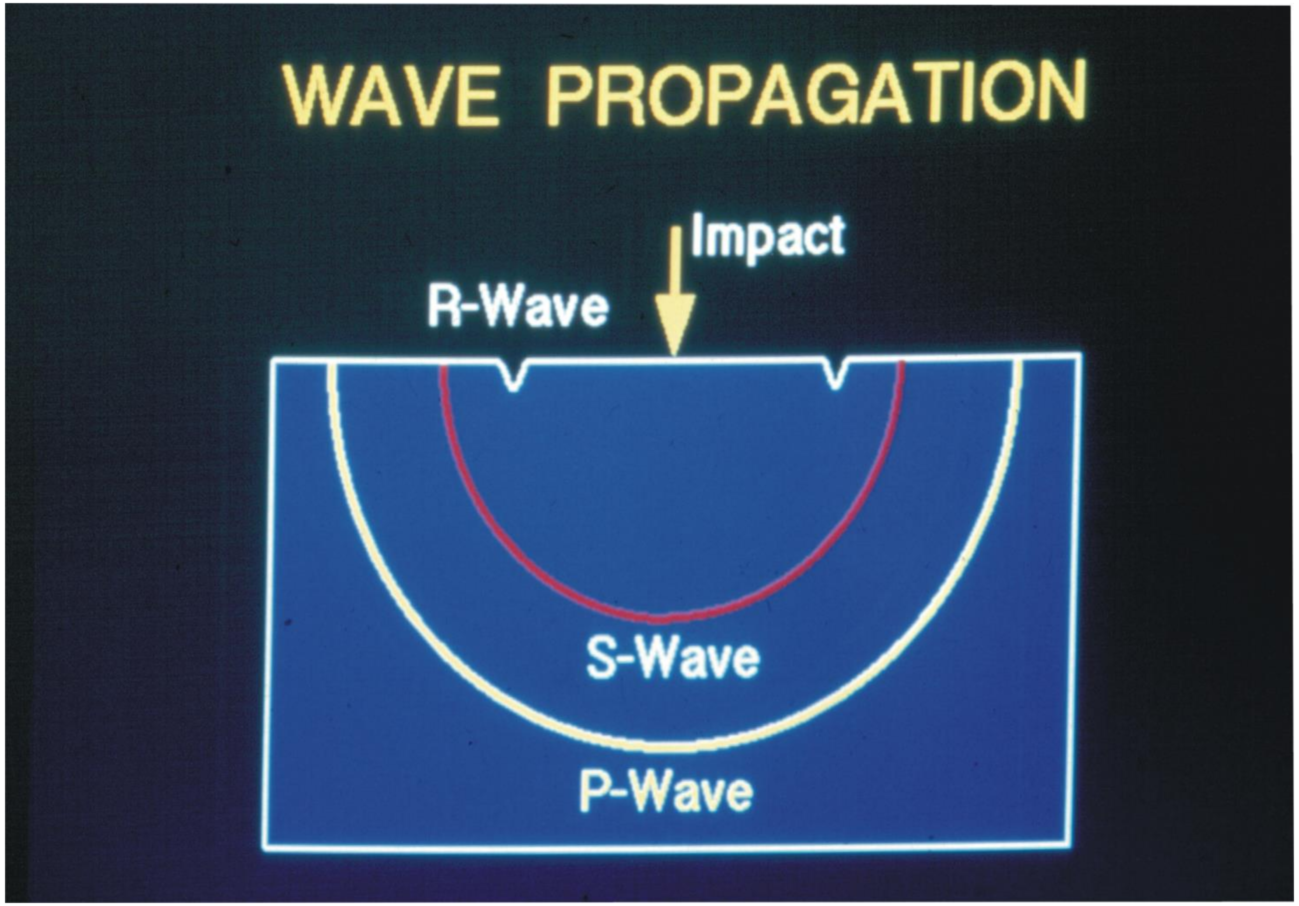
UPV/SPV Test

- Using 2 transducers - source and receiver
- Measure signal time and signal amplitude between the source and receiver (transmission test)
- Calculate concrete compression wave velocity (Vp)
- SPV uses an impact source rather than piezo transducer

Vp = Distance/Time

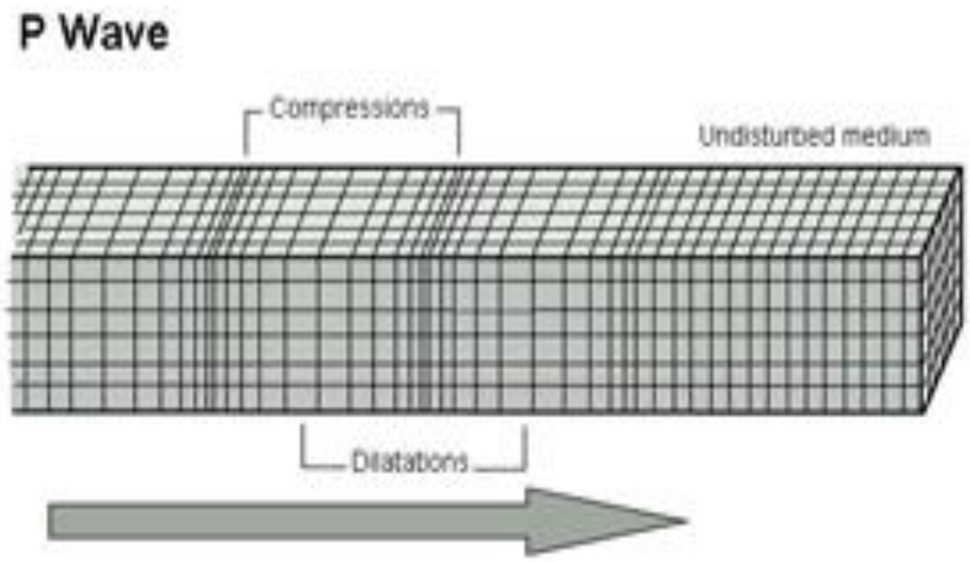


Physics – Wave Propagation (3 Wave Modes)

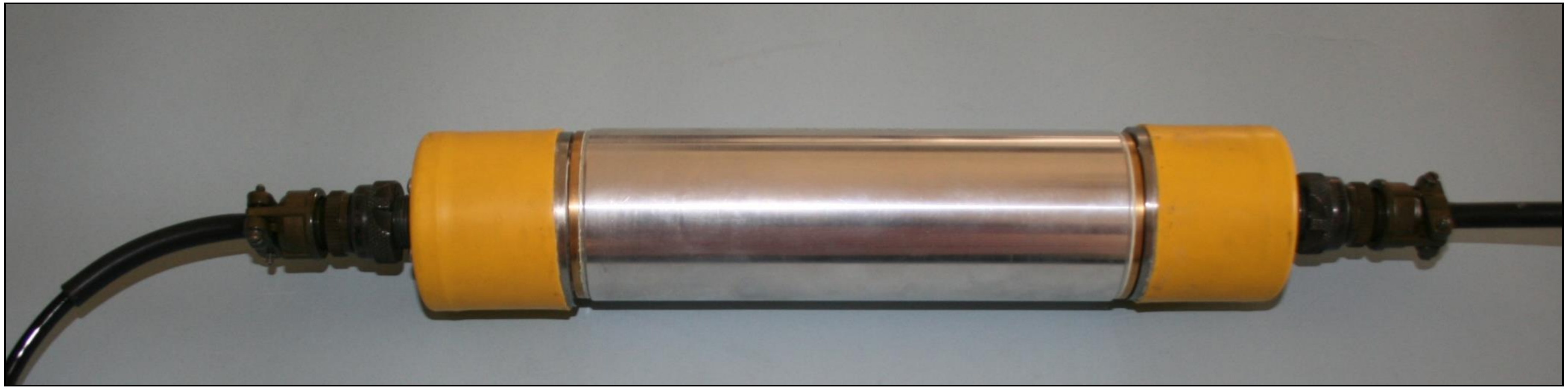


Physics – Primary Compressional Waves

The particle motion associated with compressional waves can be described as vibration parallel to the direction of wave travel.



UPV Test Procedure - Calibration

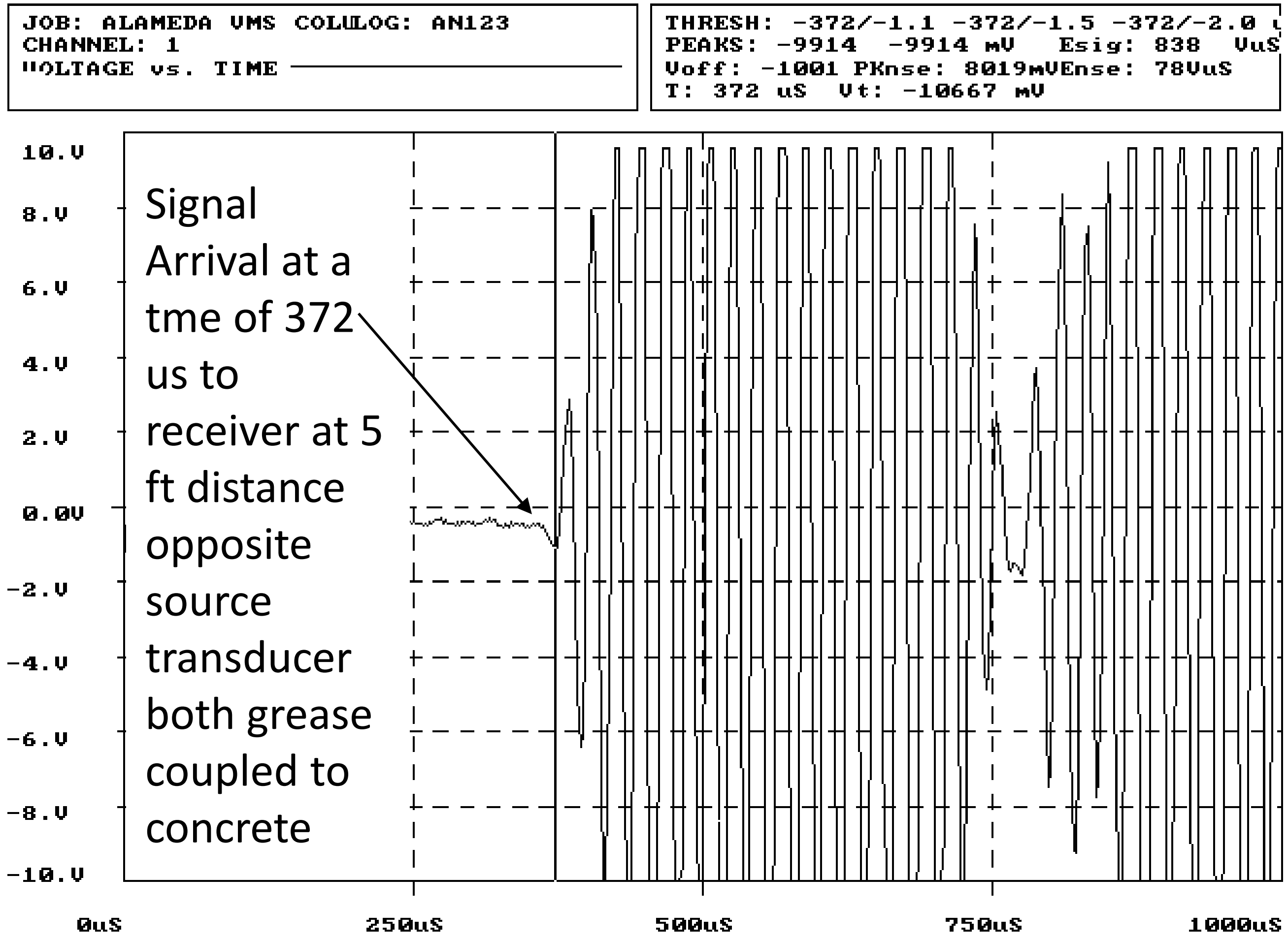


Case Study I - UPV Tests to Detect Honeycomb Void in Concrete Columns

54 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

Example UPV Test Result



Sound Concrete with Good Signal at 372 us and Pulse Velocity of 13,500 ft/s

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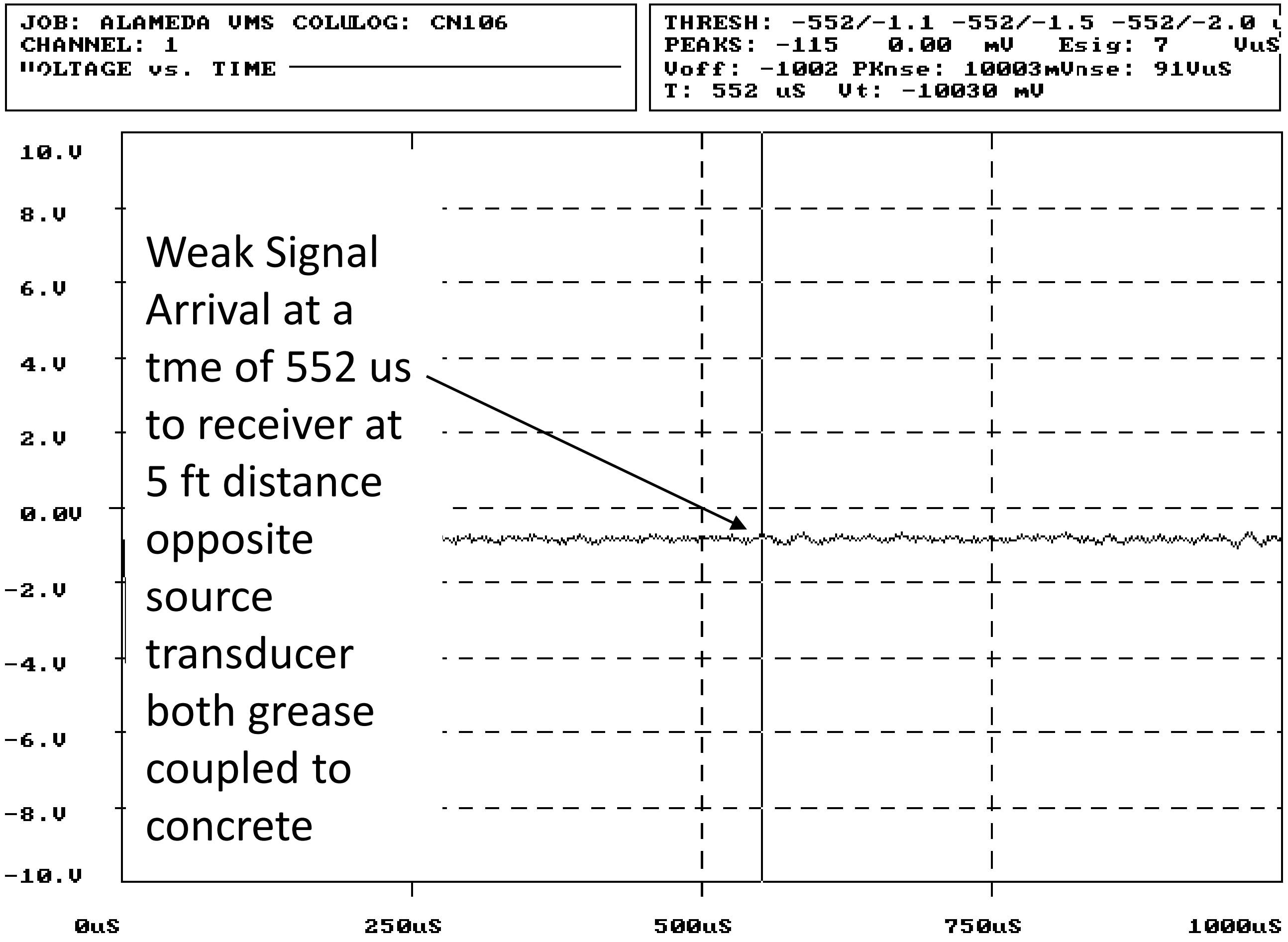
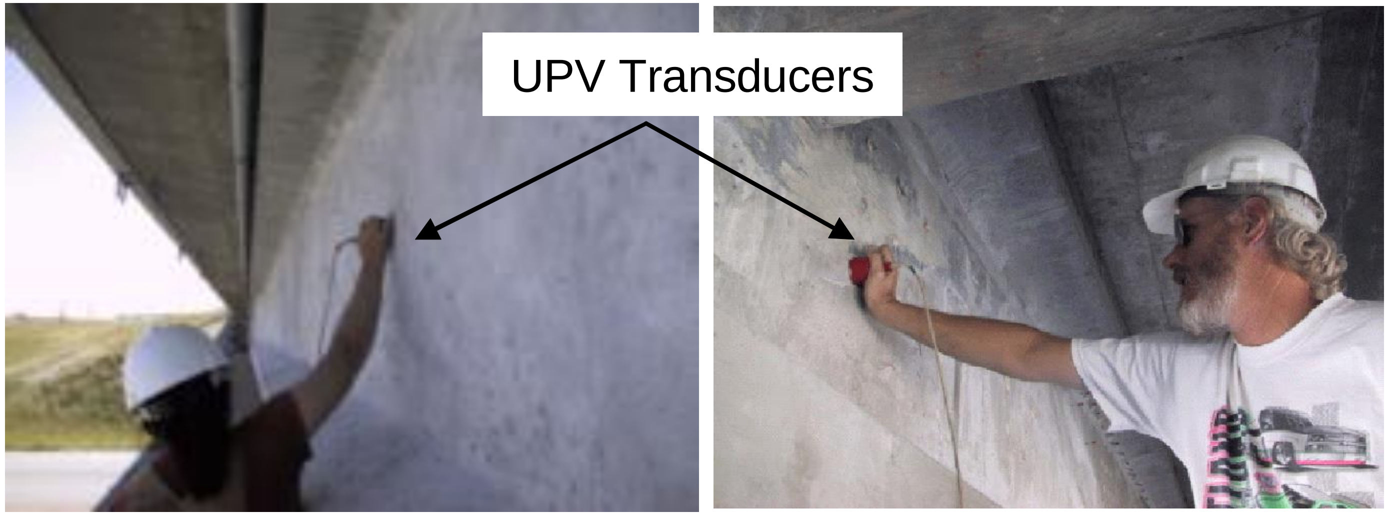


Honeycomb/Void Concrete with Weak Signal at 552 us and Pulse Velocity of 9,100 ft/s

Case Study II - Quality Assurance of Crack Repair

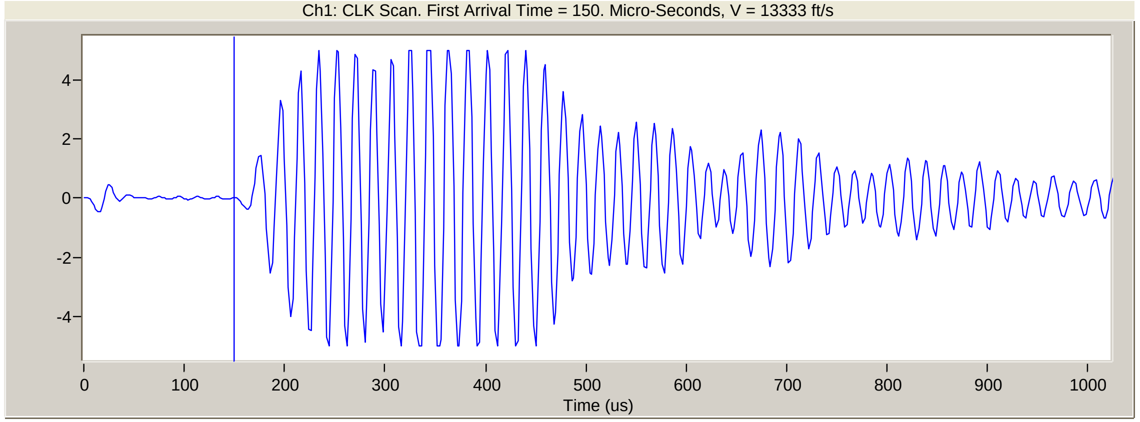

Bridge Girder with Cracks and Spalls


Epoxy Injection for Crack Repairs

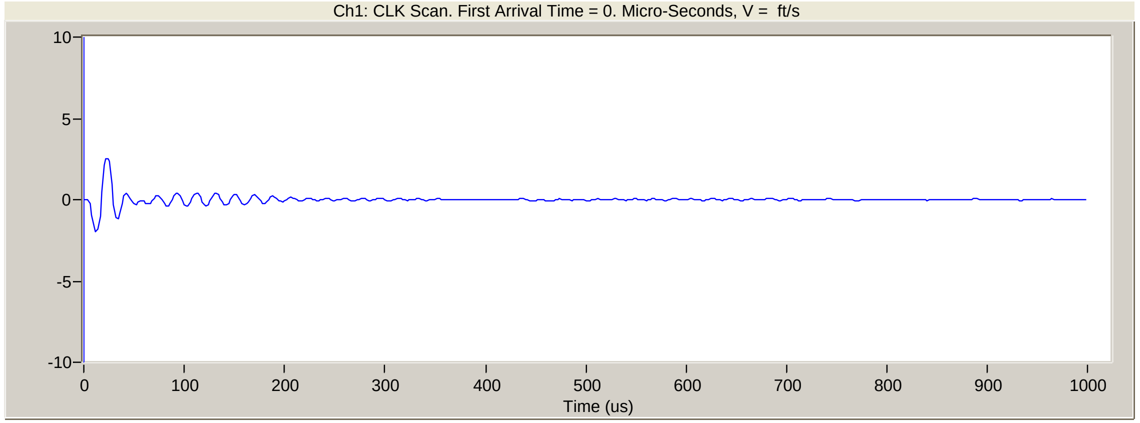


Ultrasonic Pulse Velocity to Assure the Quality of the Repair

Case Study III - UPV Tests to Detect Freeze-Thaw Damage in Concrete Columns

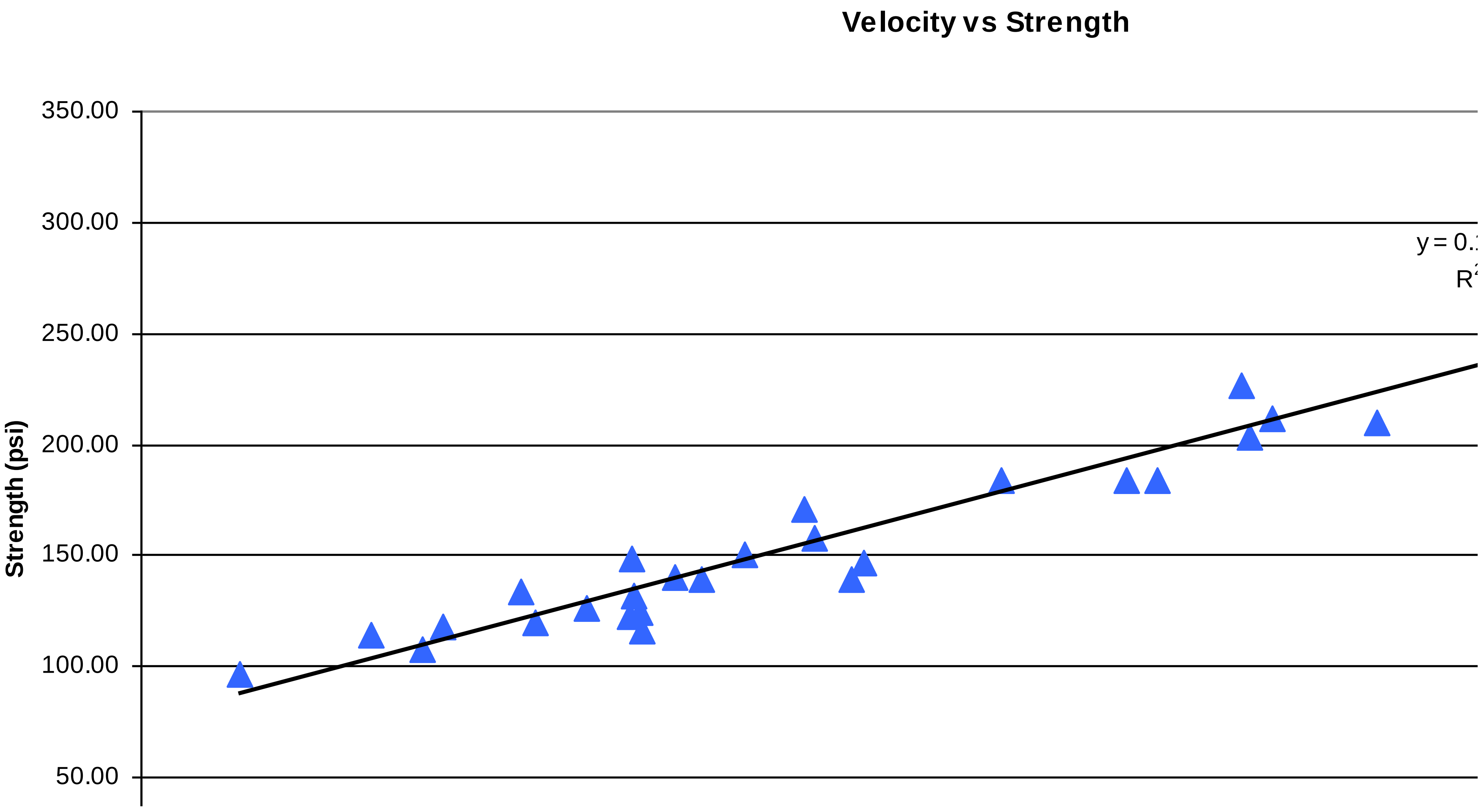


UPV Test Results from a Sound Location



UPV Test Results from Severe Deteriorate Concrete

Strength Correlations



UPV/SPV Test Advantages and Limitations

- Advantages
  - Easy field procedure
  - Easy data analysis
- Limitations
  - Requires 2 accessible sides
  - Depends on the surface condition

SPV (Sonic Pulse Velocity) Testing

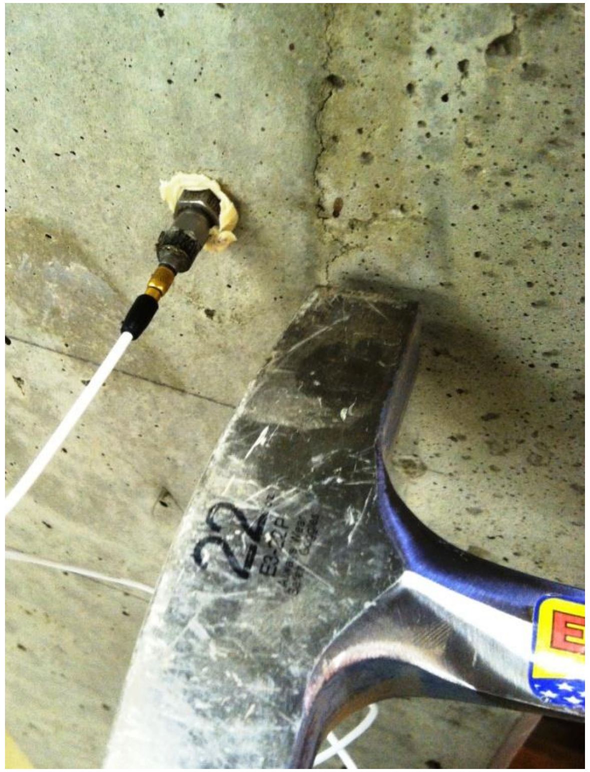
- SPV is a low-frequency/high energy version of UPV.
- Available on all NDE-360 systems with UPV (SPV mode touch button)
- Requires an instrumented hammer or a steel hammer and sensor as a source
- Can be done using two UPV transducers and a hammer

SPV Test Setup

Hammer Source with UPV Transducer Trigger

UPV Transducer Used as SPV Receiver

Alternate SPV Test Setups

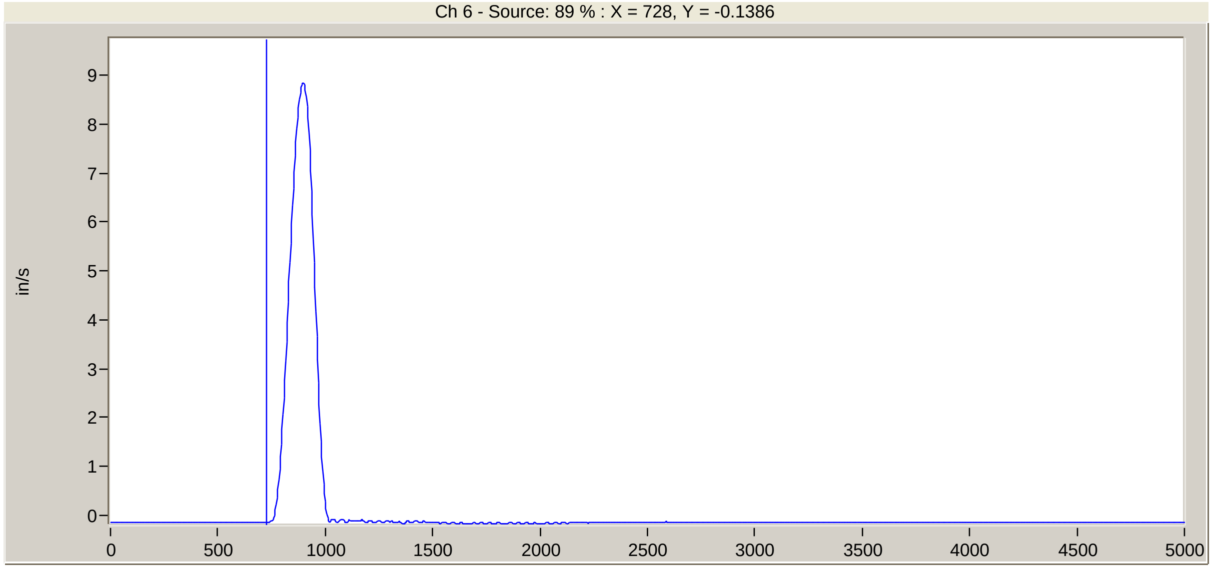


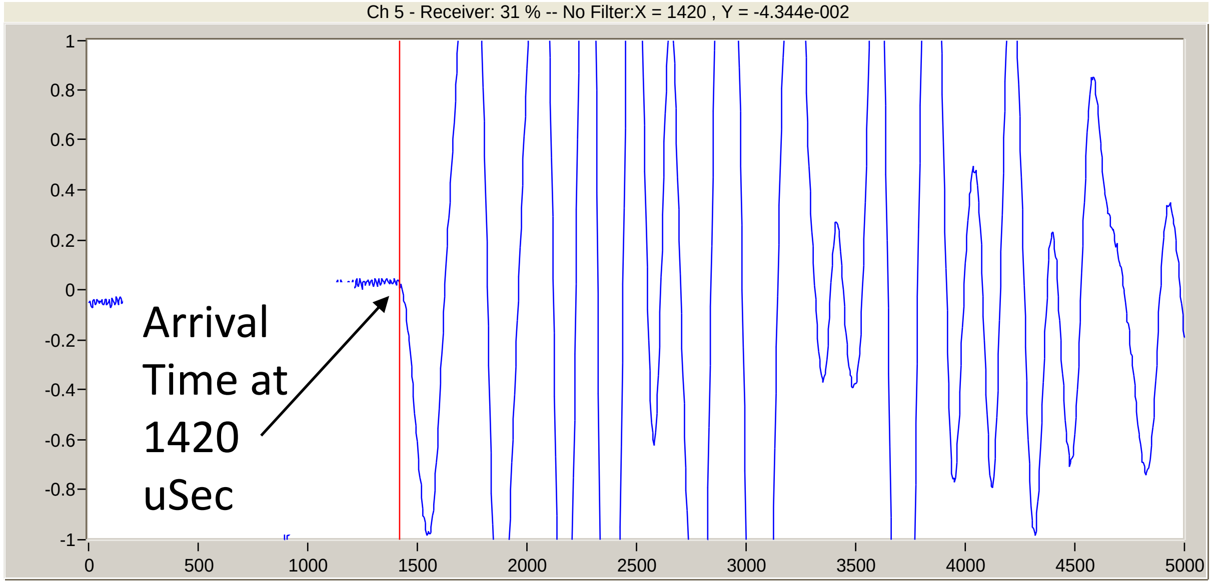
Hammer Source with
Accelerometer Trigger

0.2 Pound Instrumented
Hammer Trigger

- SPV is normally used on large structures – pedestals, mat foundations, dams, etc.
- Simplest setup and use is with an instrumented hammer and accelerometer or UPV receiver.
- Measures travel time just like UPV, but total time is measured by subtracting trigger time from receiver time.

SPV Data Example





SPV Sample Data – top trace = hammer impact (trigger) signal, Trigger time = 728 uSec

Bottom trace = receiver signal (with cross-coupled source signal). SPV arrival time = 1,420 uSec

SPV Velocity = 8.4 ft/(1420-728 uSec)= 12,138 ft/sec

Ultrasonic, Sonic and Seismic Tomography

Ultrasonic, Sonic and Seismic Tomography - Theory

- Seismic Tomography is Similar to a CAT Scan in the Medical Profession
- Common Types
  - **Travel Time Tomography**
    - Governed By Material Velocity
  - Attenuation Tomography
    - Associated with Dispersion of Seismic Energy and Frictional Loss
- Olson Engineering Methods
  - Ultrasonic Pulse Velocity (UPV) and Sonic Pulse Velocity Tomography
  - Crosshole Tomography (CT)
- Practical NDE Applications
  - Investigations of voided or questionable concrete in drilled shafts, piles, piers, columns, walls, etc.

Travel Time Tomography Governing Equations

- 3D Elastic Wave Equation

$$\rho \ddot{\mathbf{u}} = \mathbf{f} + (\lambda + 2\mu)\nabla(\nabla \bullet \mathbf{u}) - \mu\nabla \times (\nabla \times \mathbf{u})$$

where:

– λ and μ are the Lamé parameters, which describe the elastic properties of the medium

– ρ is density

– f is the source function

– u is displacement

- Inverse Problem

where: $d = Gm$

– d is the travel time data

– m is the model of the medium

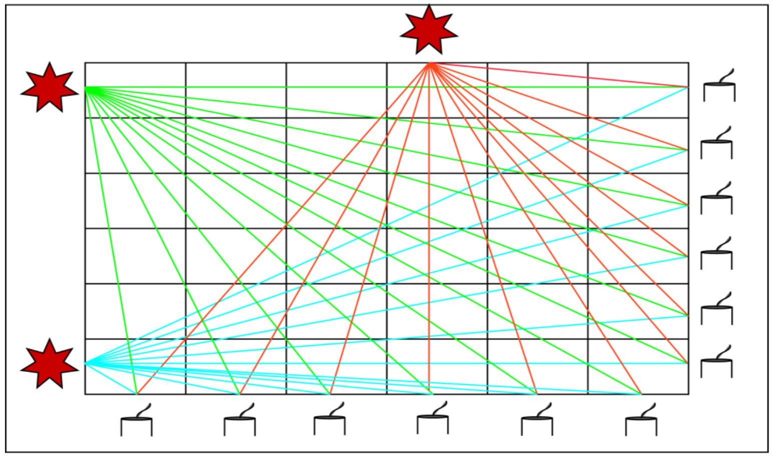
– G relates the data to the model

GeoTomCG

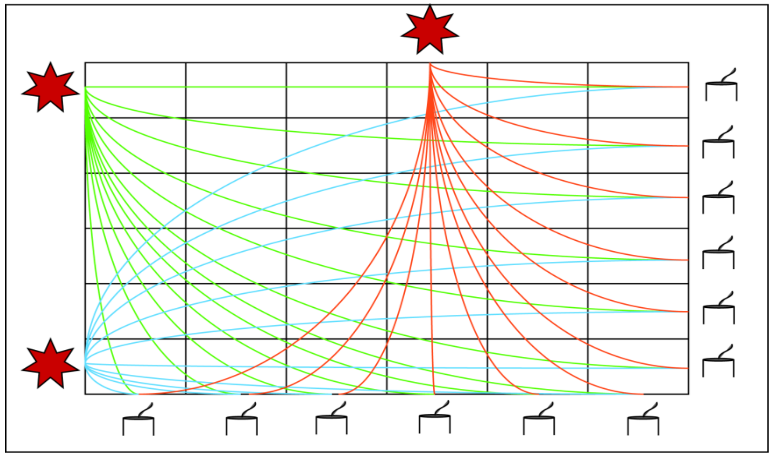
- Inversion Software used by Olson for Tomographic Investigations (CT and UPV).
- Created by **GeoTom, LLC**
- Capabilities:
  - Source-to-receiver travel times can be analyzed to calculate velocities
  - Amplitudes can be analyzed to calculate attenuation coefficients
  - Source and receiver positions can be in any configuration within a 3-D grid
  - The tomographic analysis calculates velocity and/or attenuation at points within the grid
  - Anisotropy can be specified for each point of the grid
  - Ray Paths can be straight or curved

Velocity Tomography – Ray Paths - Straight vs. Curved

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.

Ultrasonic Pulse Velocity with Tomographic Velocity Analysis for Investigation of Honeycomb/Void in Concrete Highway Sign Column

Ultrasonic Pulse Velocity for Investigation of Honeycomb/Void in Concrete Highway Sign Column

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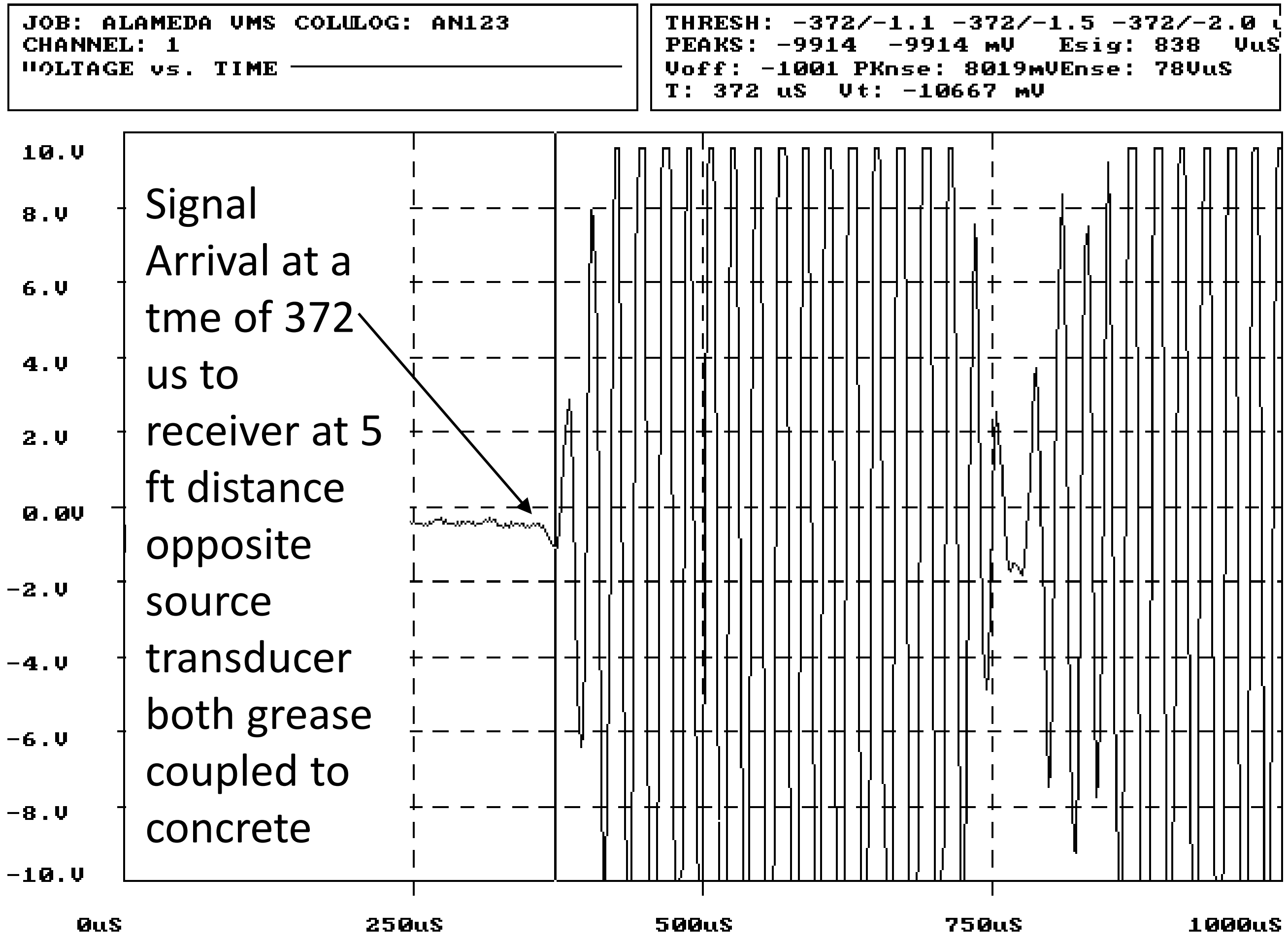

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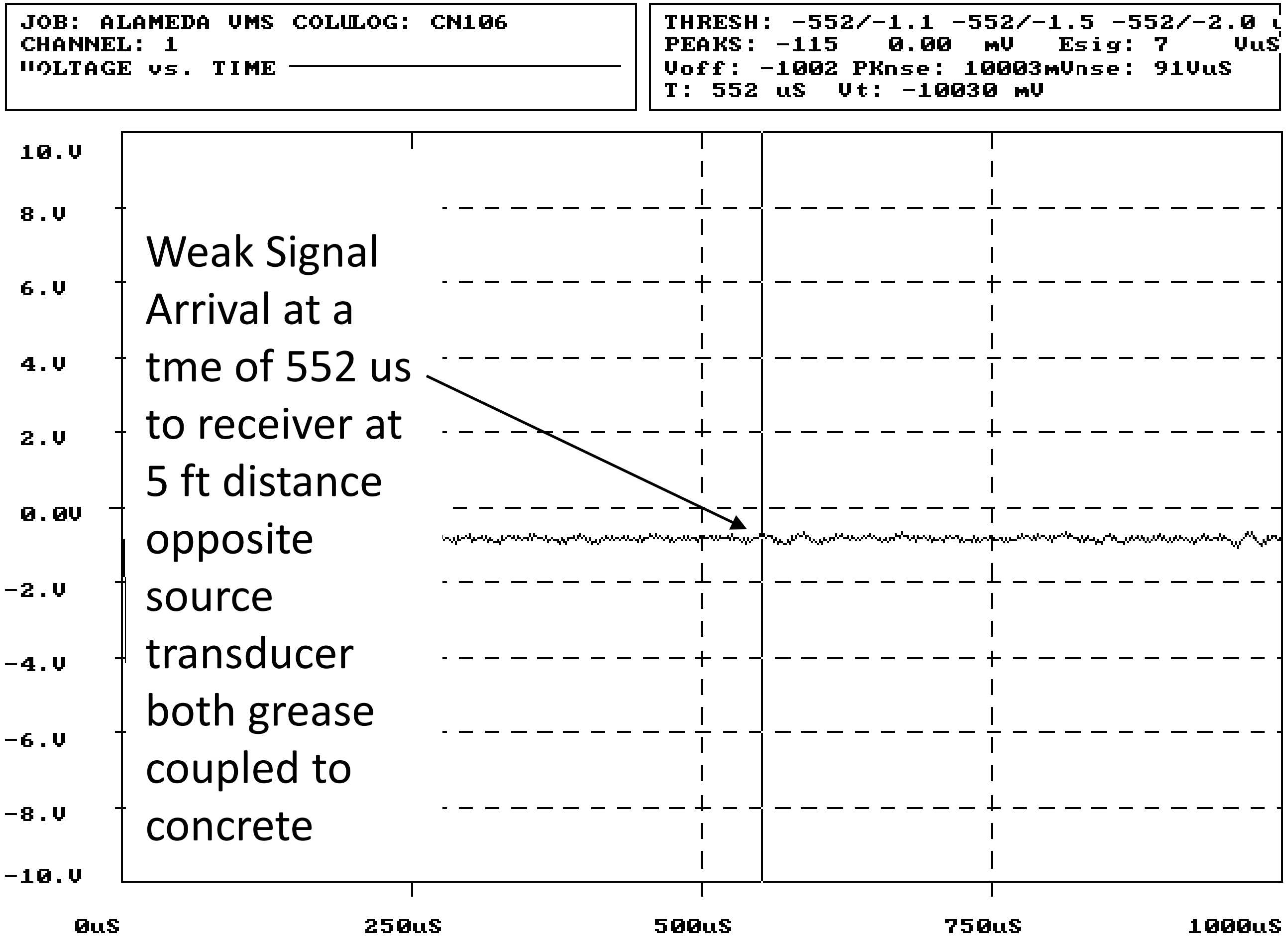
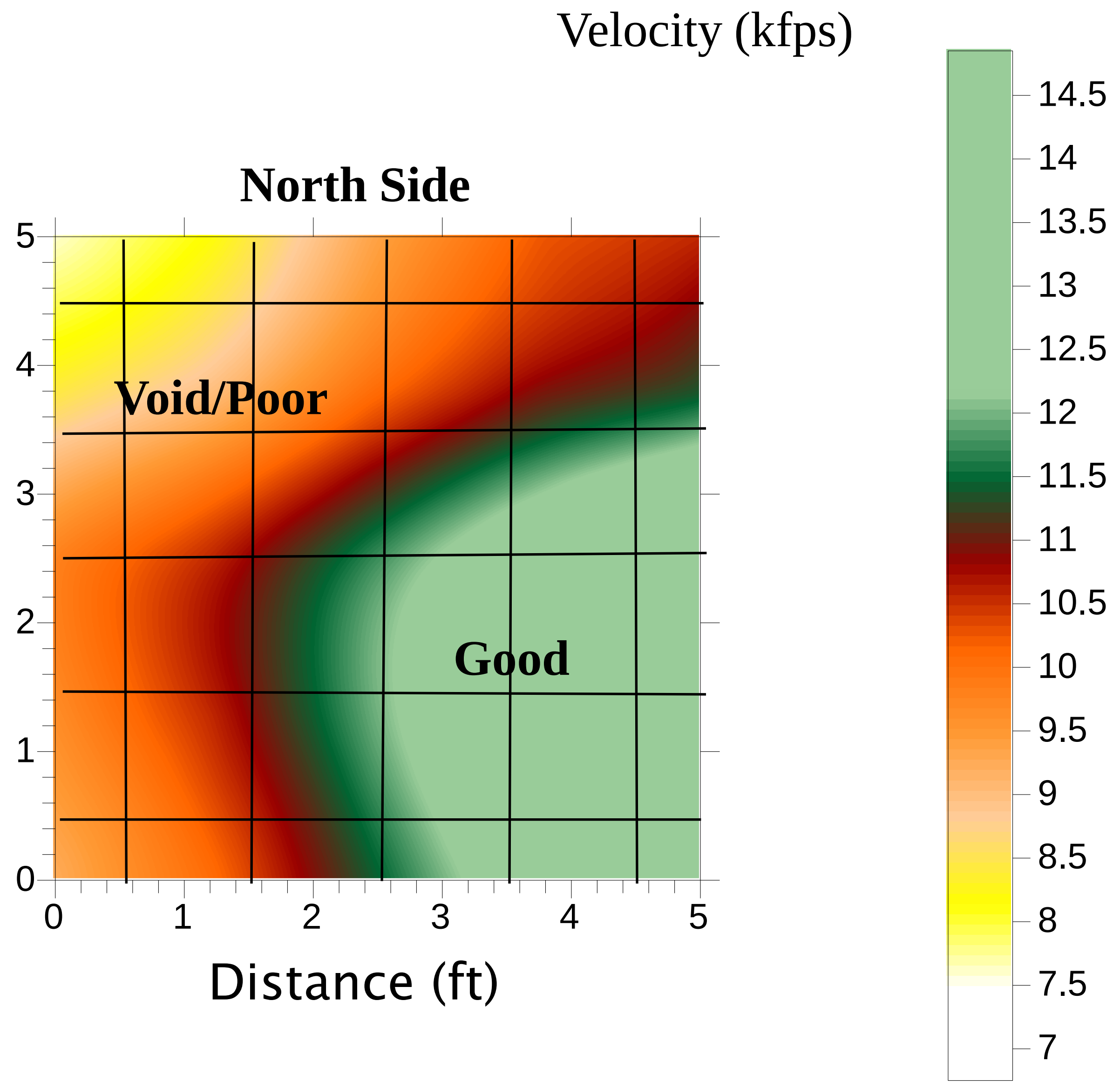


Honeycomb/Void Concrete with Weak Signal at 552 us and Pulse Velocity of 9,100 ft/s

Ultrasonic Tomography for 2-D Cross-Sectional Horizontal Images of Internal Void/Honeycomb Conditions in Highway Sign Column

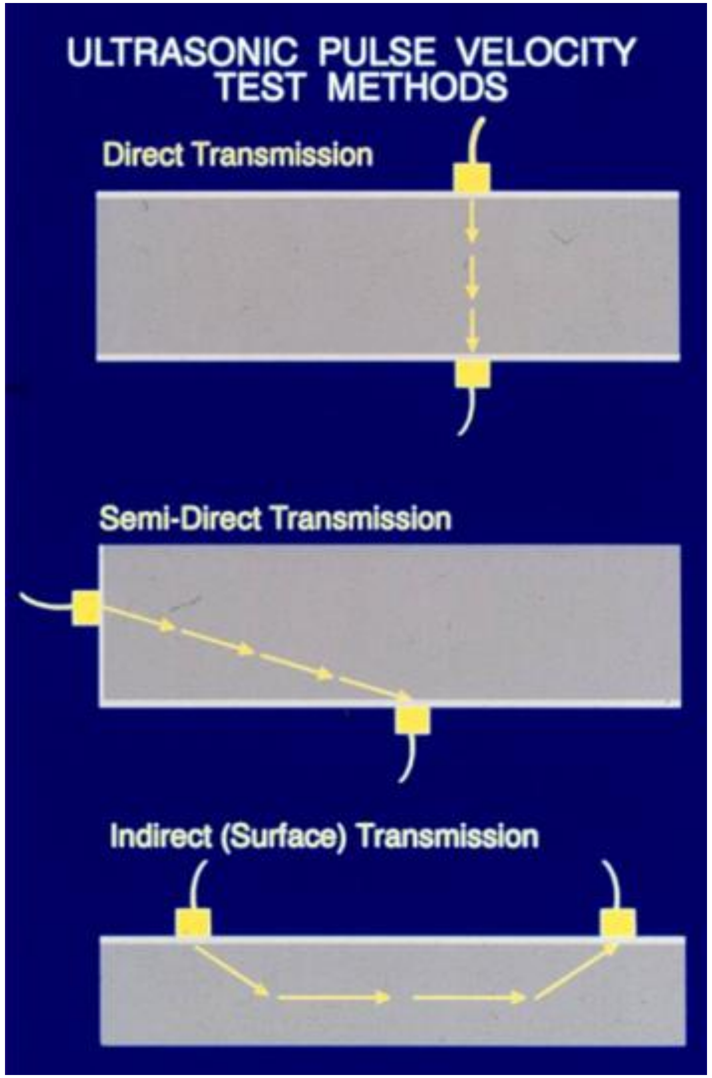
- 2-D Velocity Tomogram of Column showing slow velocity zones indicative of internal poor quality concrete due to poor consolidation in a horizontal slice and good concrete

- 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



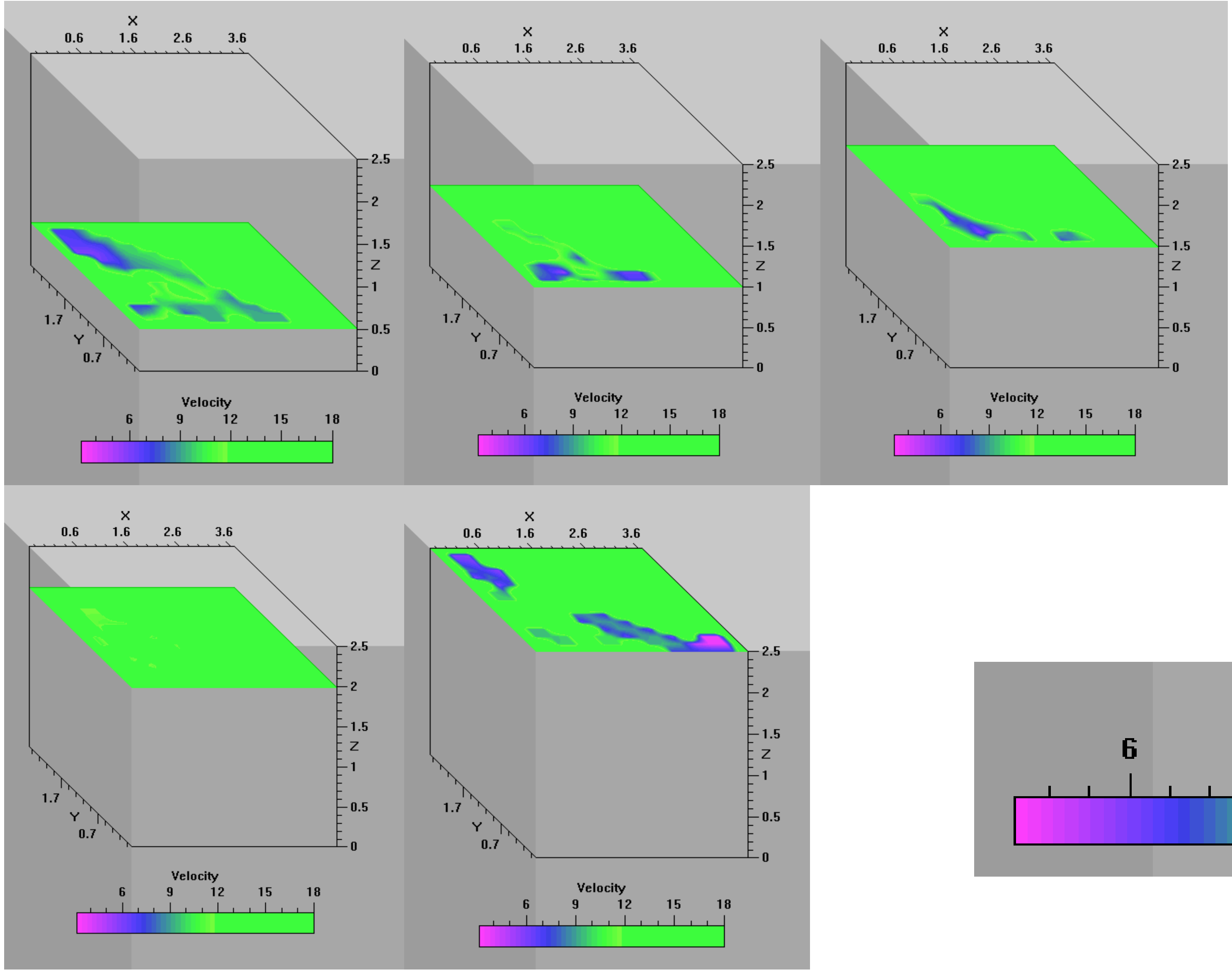
Ultrasonic Pulse Velocity for Investigation of Honeycomb/Void on I-35W Concrete Bridge Pier
Minneapolis, Minnesota

Images of Surface Honeycomb and UPV Grid Layout

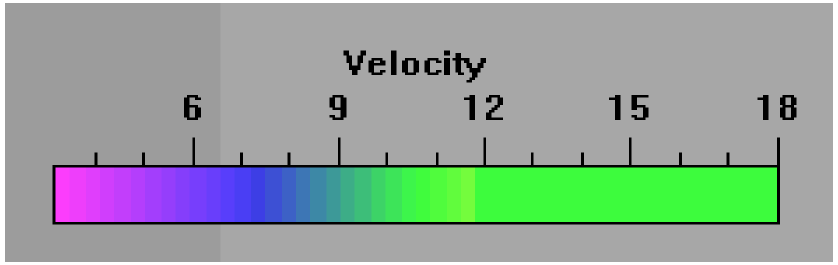


Semi-Direct UPV Testing was performed on the corner of this column – note lithium grease spots for coupling of 54 kHz transducers to concrete

2-D Tomography Slices shown in a 3-D Volume



Distances are in Feet (ft), Velocities are in kilo-feet per second (k-ft/sec)



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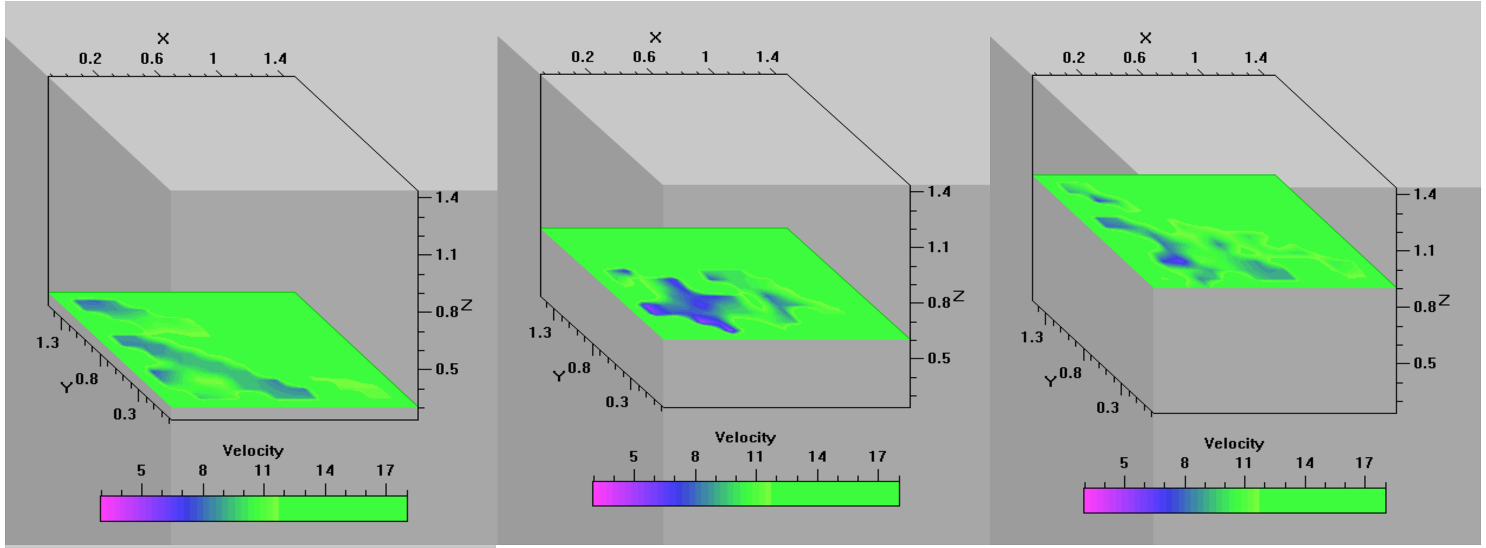

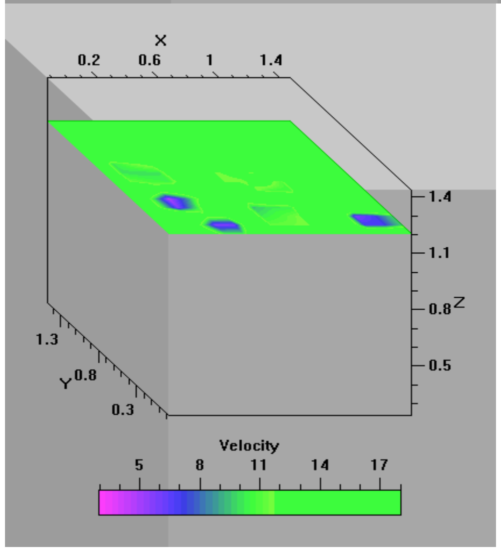

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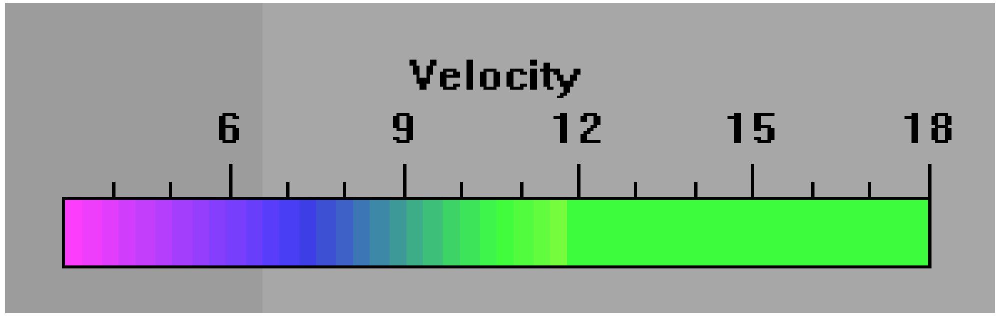


Ultrasonic Tomography Training, Advantages and Disadvantages

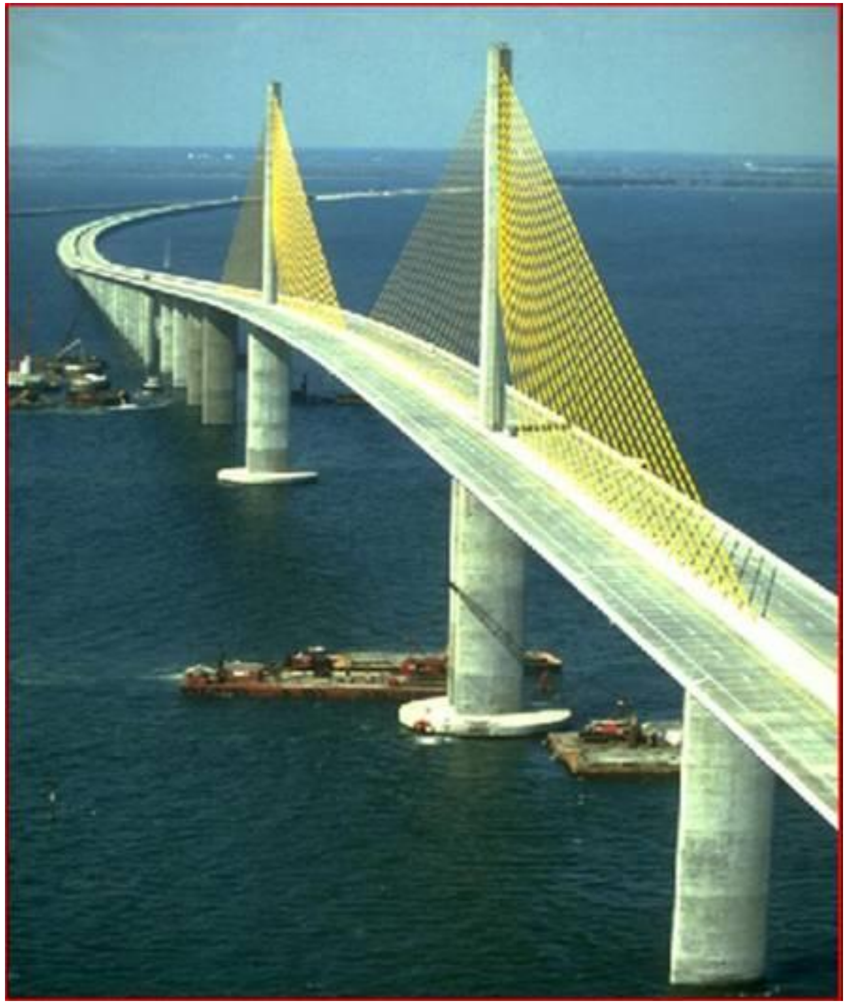
- Requires extensive training and experience for analysis, but field data collection less complicated
- Image internal flaws in 2-D and now 3-D fashion with angled and direct tests
- A picture is worth a thousand words sometimes and velocity tomograms provide an image of internal void, cracking and honeycomb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

Impact Echo Scanning for Grout Void Detection in Post-tensioned Bridge Ducts to mitigate Corrosion Risk

- More than 130,000 post-tensioned bridges that contain steel tendons
- If ducts are not fully grouted, water can enter the steel tendons resulting in corrosion of tendons

Poorly Grouted Duct – Tendons Exposed (from Video borescope)

Sunshine Skyway Bridge –Tampa Bay Florida – Corrosion of Looped "U" Pier Tendons

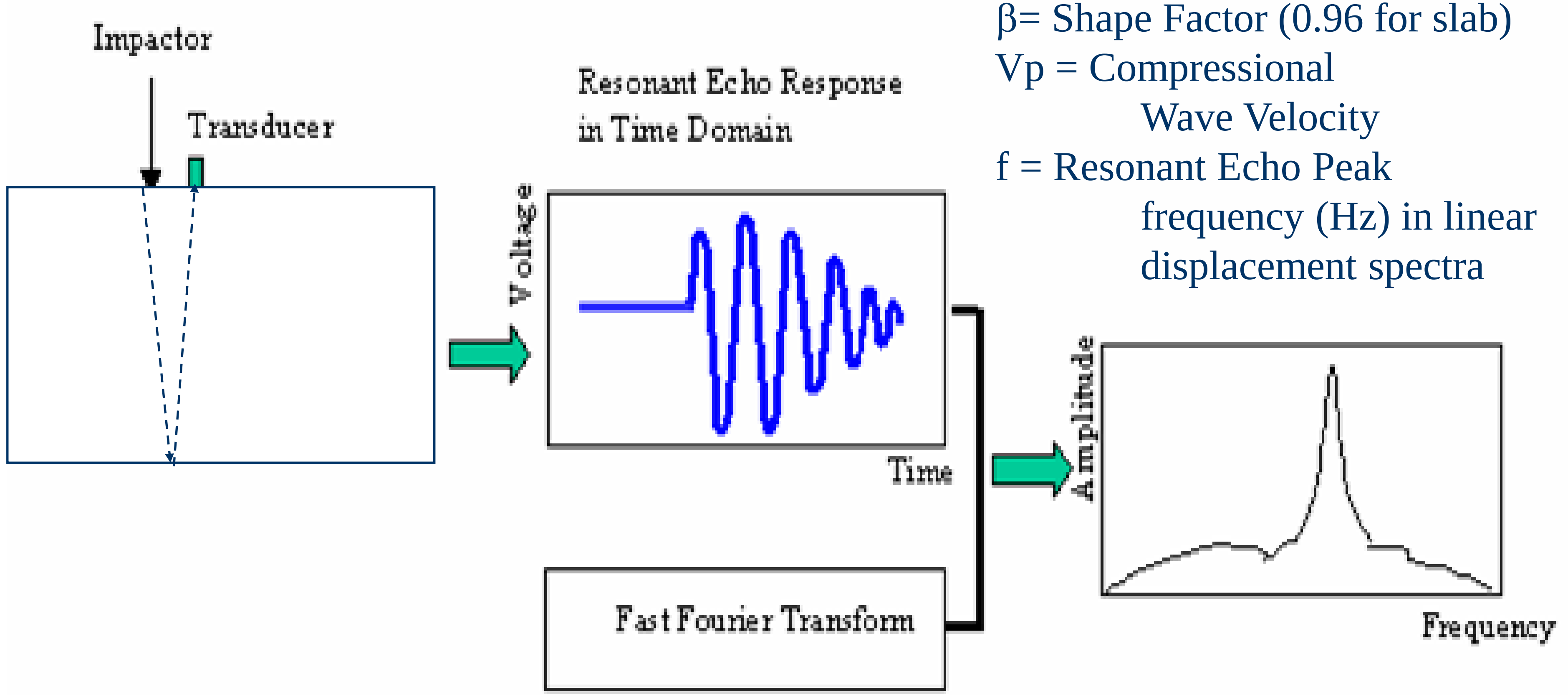


Courtesy of Florida Department of Transportation

Impact Echo Test

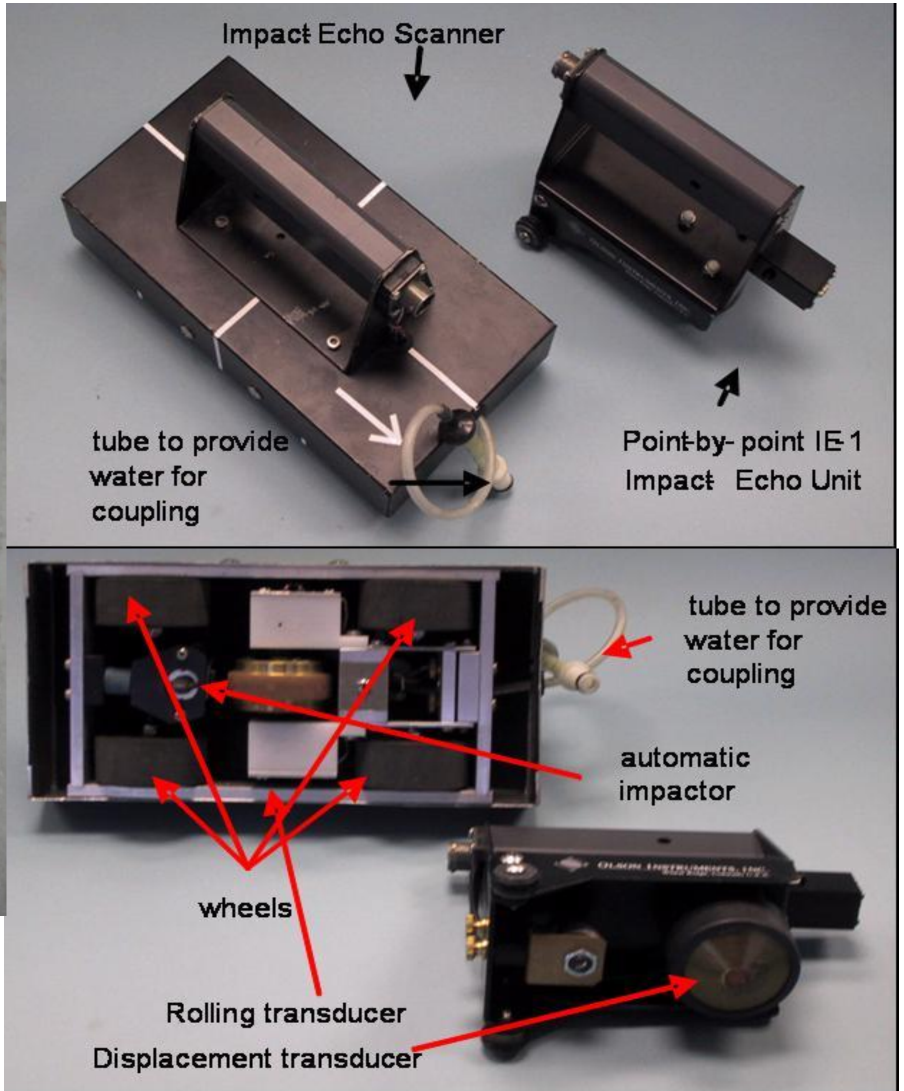
$D = \beta V_p/(2 * f)$

- D = Thickness
- β= Shape Factor (0.96 for slab)
- Vp = Compressional Wave Velocity
- f = Resonant Echo Peak frequency (Hz) in linear displacement spectra



Impact Echo Scanner (IES)

- Add wheels to the unit
- Add a rolling transducer
- Calibrated to test every 25 mm or 1” interval
- Speed ~ 20 ft in 1 minute

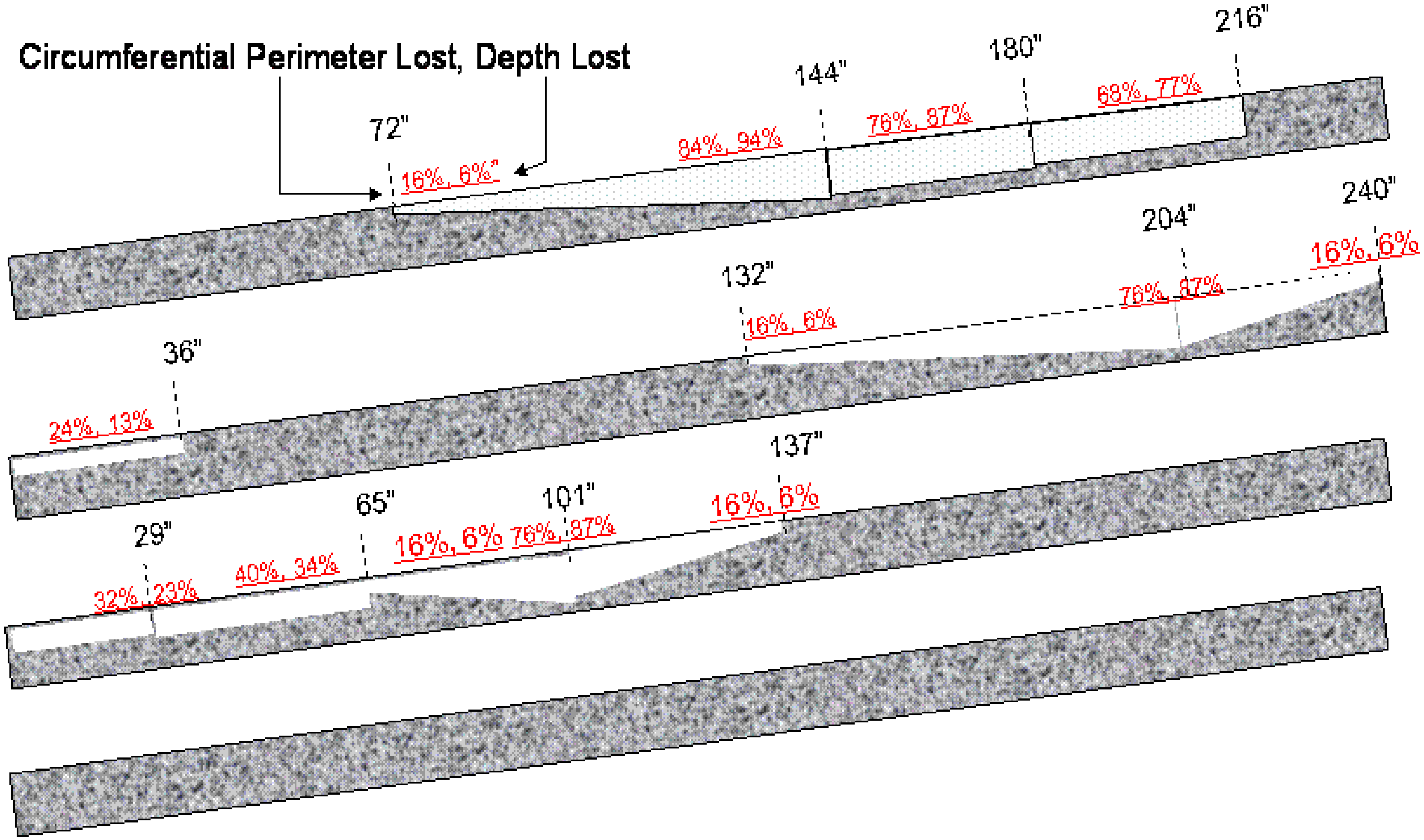


NCHRP IDEA Research Project – Specimen# 1

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

Grout Defect Simulation with closed-cell Styrofoam Void

Defect Scheme – South Wall

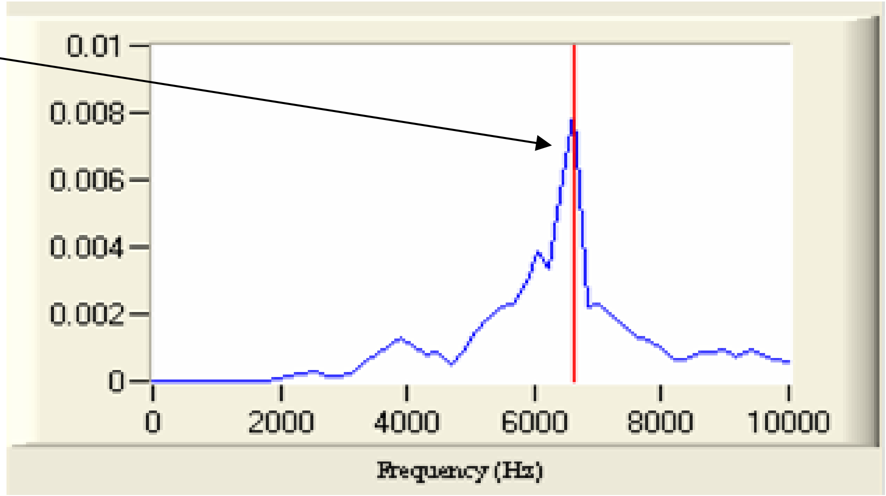


Interpretation of IES Data

- IES was performed every 6 inches vertically across the ducts
- A direct echo from void has not been observed from the tests
- The only indication of void is a downshift in the dominant frequency resulting in an increase in thickness
- Three dimensional surface plots are helpful with interpretation and visualization of defects

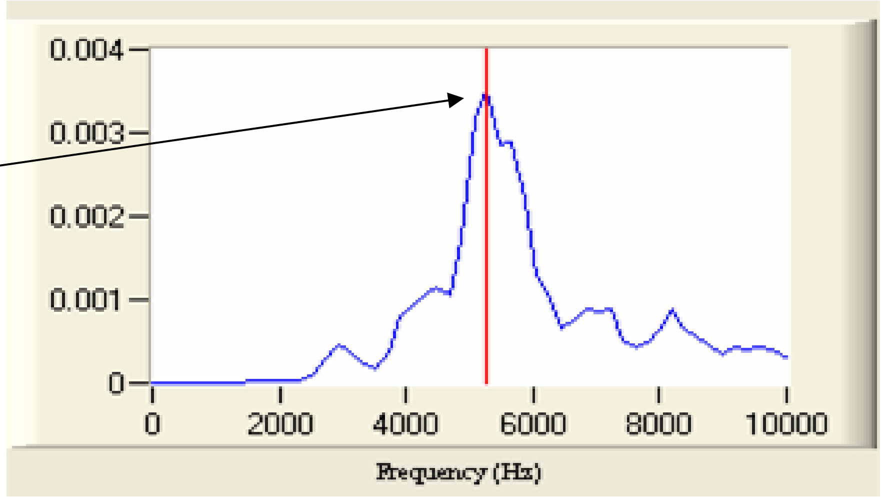
Research Results – NCHRP IDEA Program

- Fully Grouted Duct
  - Frequency peak = 6,445 Hz
  - Apparent Thickness = 11.17 inches

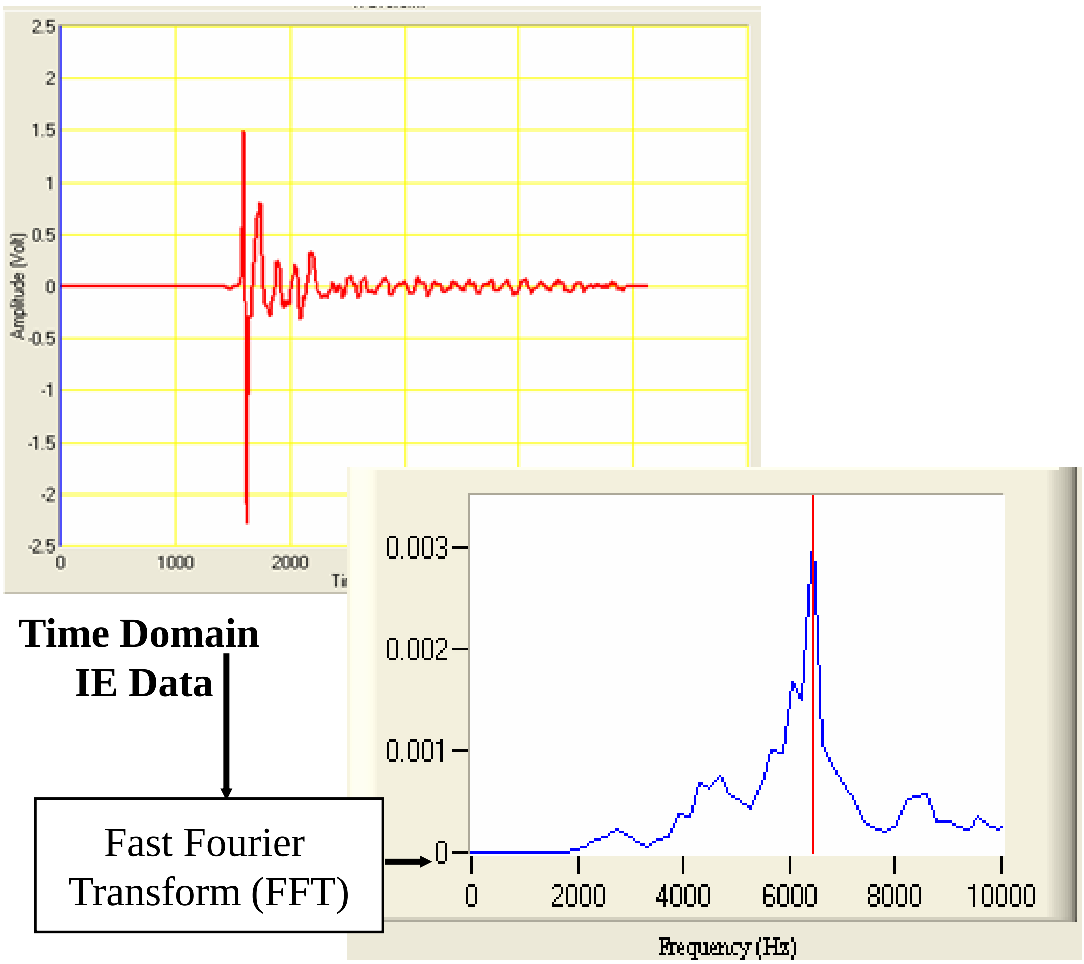


- The Void is indicated by an apparent increase in thickness due to a downward shift in the resonant echo thickness frequency because "there is a hole in it" and it is less stiff

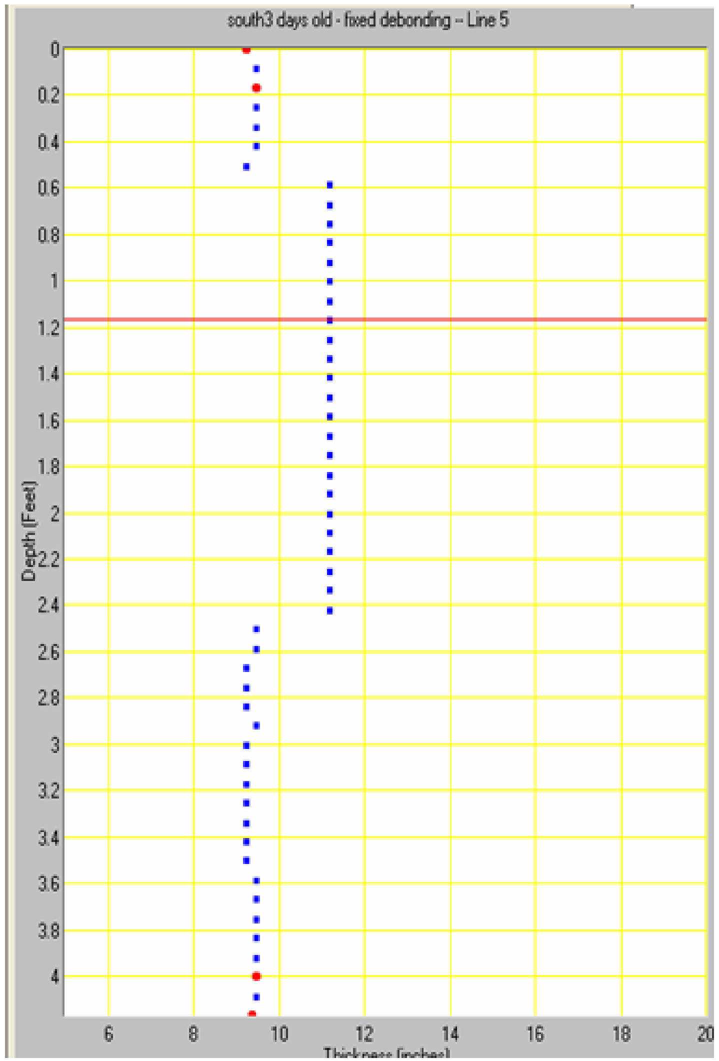
- Empty Duct
  - Frequency peak = 5,274 Hz
  - Apparent Thickness = 13.65 inches



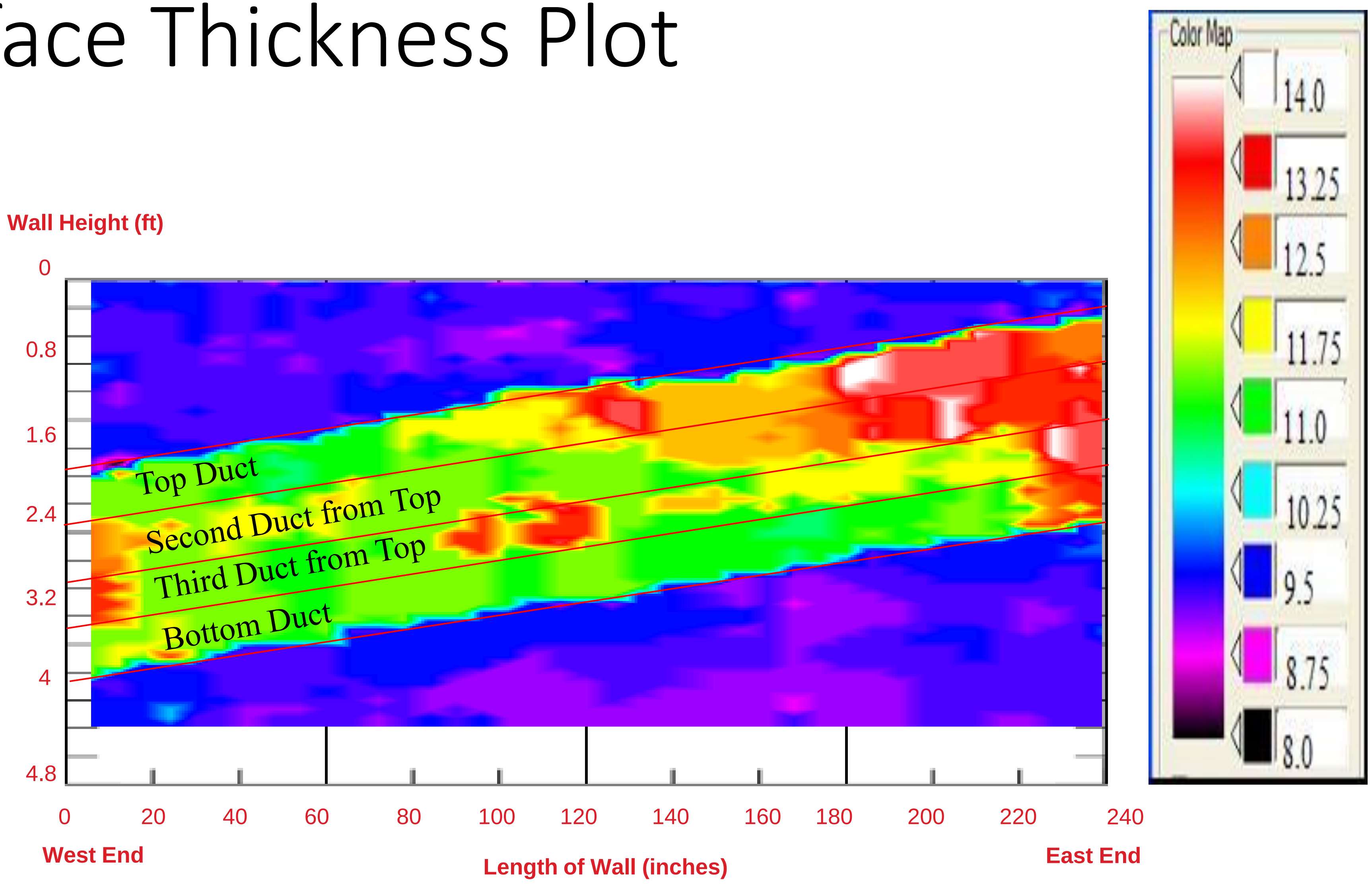
Traditional Impact Echo Results but with scanning every inch (25 mm) for grouted 3 day old duct zone



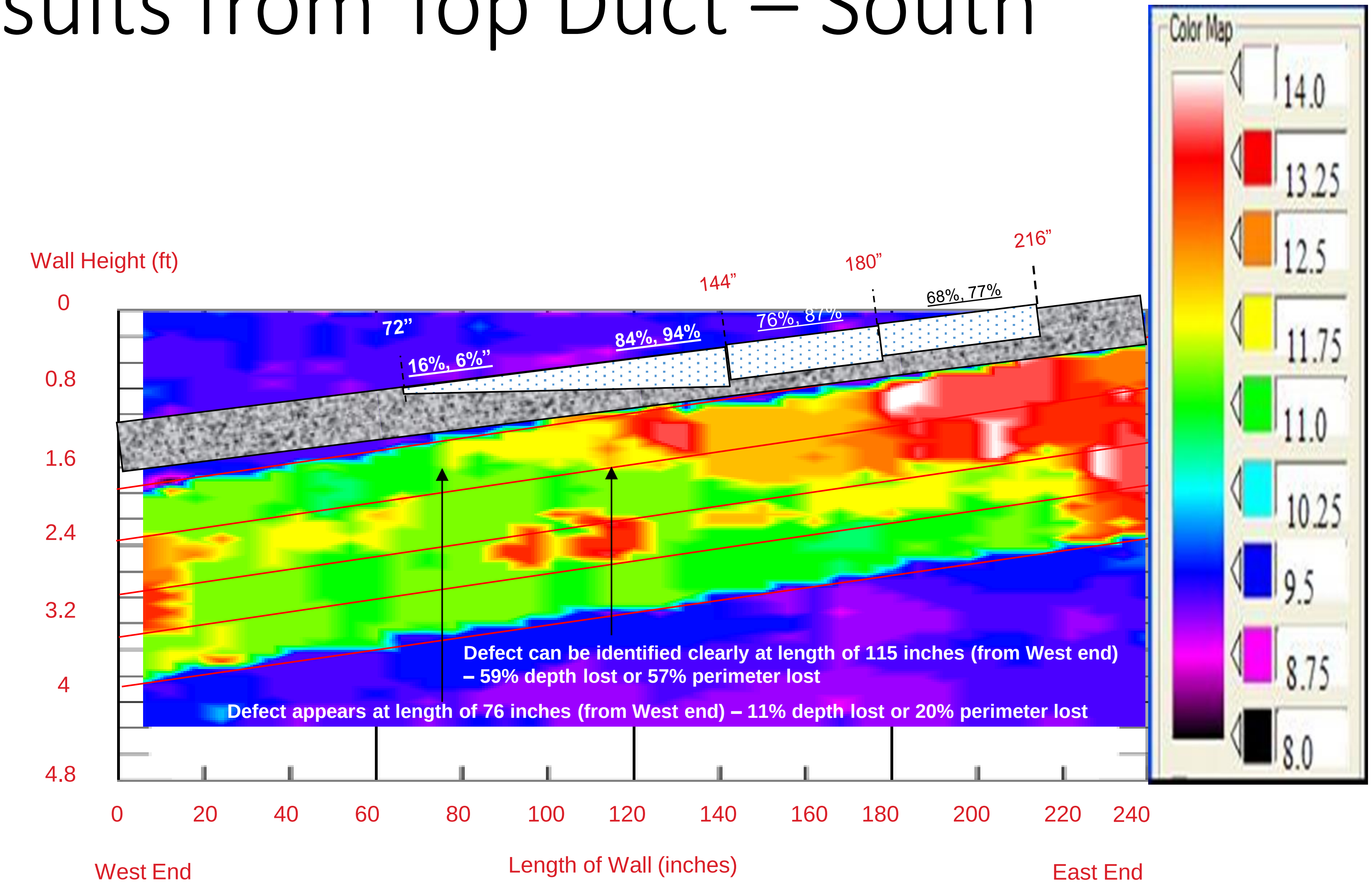
Displacement Spectrum vs.
frequency (Hz)



3D Surface Thickness Plot

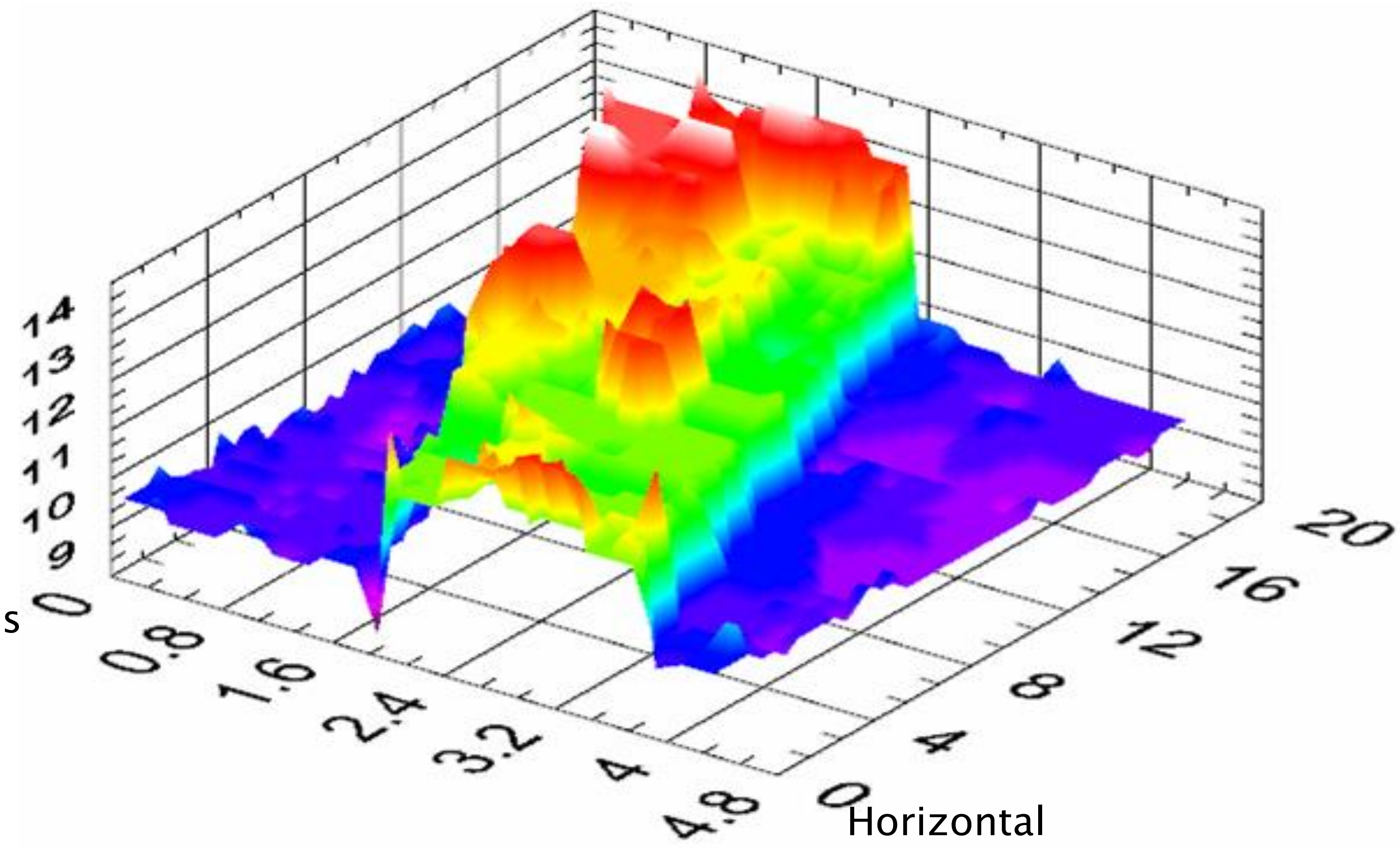


IES Results from Top Duct – South Wall



Skewed view 3-D Research Results from NCHRP IDEA Program Grant No. 102

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



IES Thickness Echo (inches)

Vertical Distance (ft) up Girder Web Wall

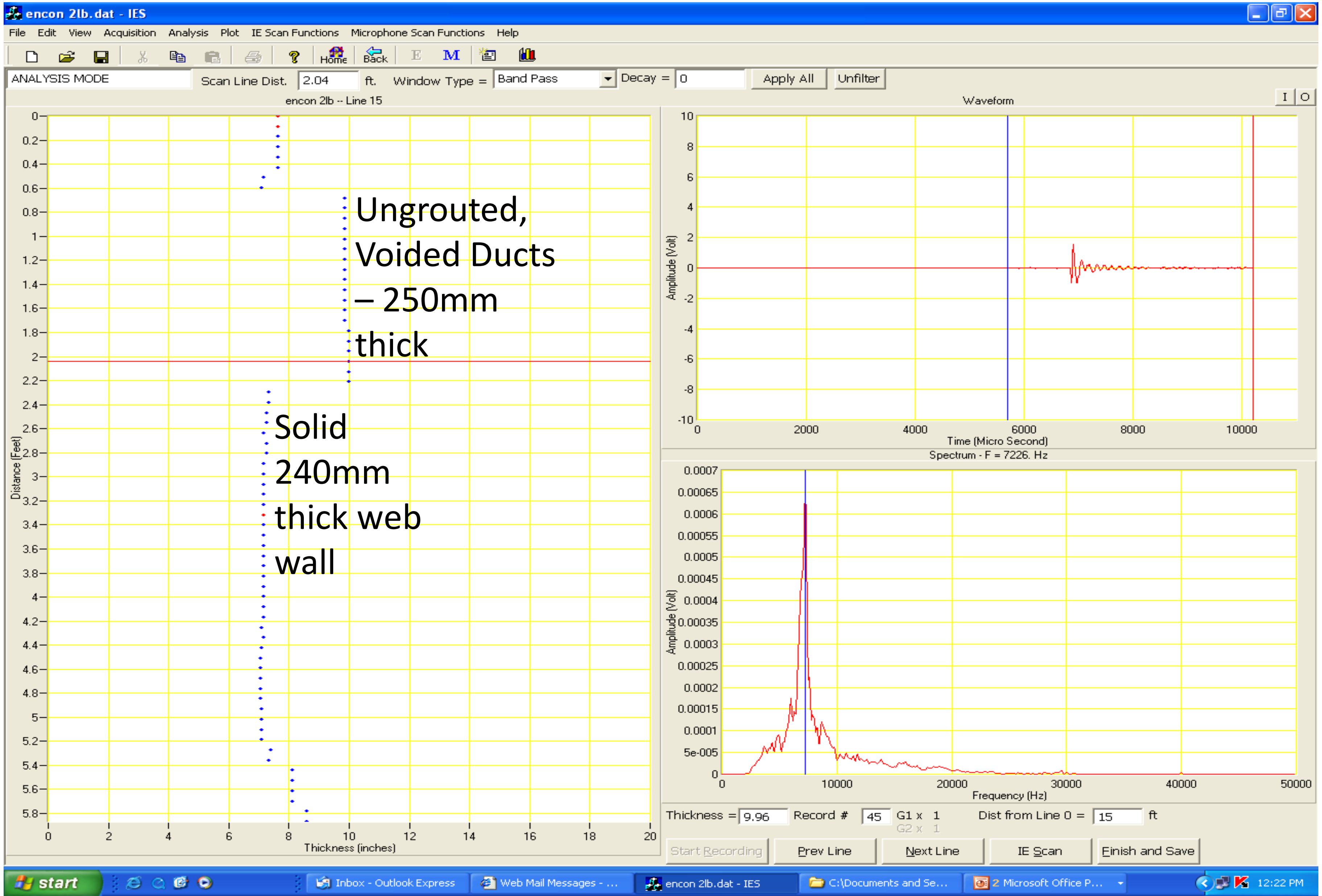
Horizontal Distance (ft) from Girder West End

Findings from the NCHRP Research

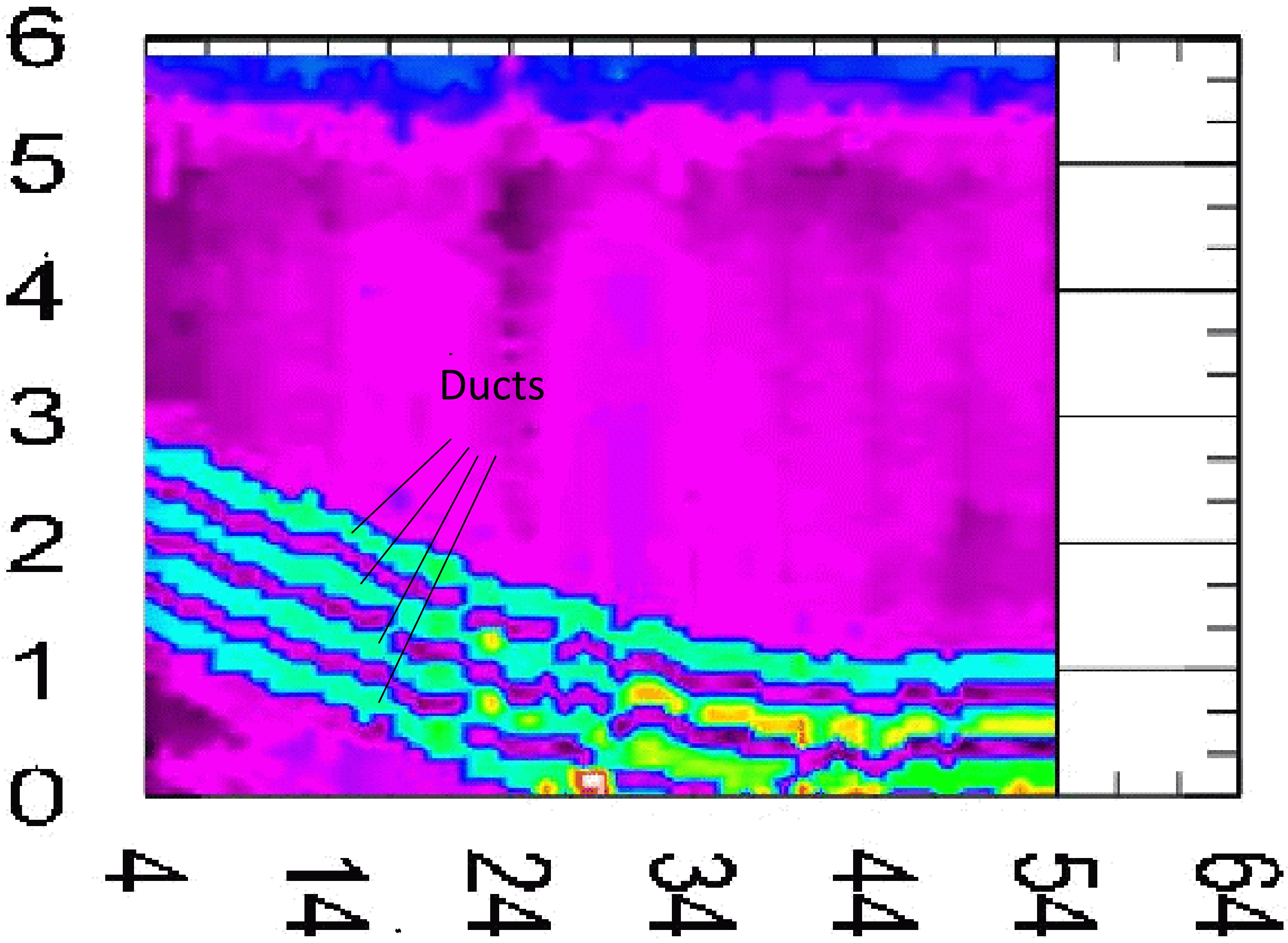
- The Impact Echo technique can be used to identify the internal grout condition
- Impact Echo Scanner (IES) accelerates the IE test process
- The use of IES makes it easier to generate the 3D surface plot
- The 3D surface plot helps in interpretation and visualization of internal grout defects
- The smallest grout defect detected from the IES surface plot is the defect with 11% depth lost or 20% circumferential lost for 4” diameter duct

New Post-Tensioned Bridge - Check Duct Grouting using Impact Echo Scanning

IE Scan of Ungrouted Girder in Precast Yard

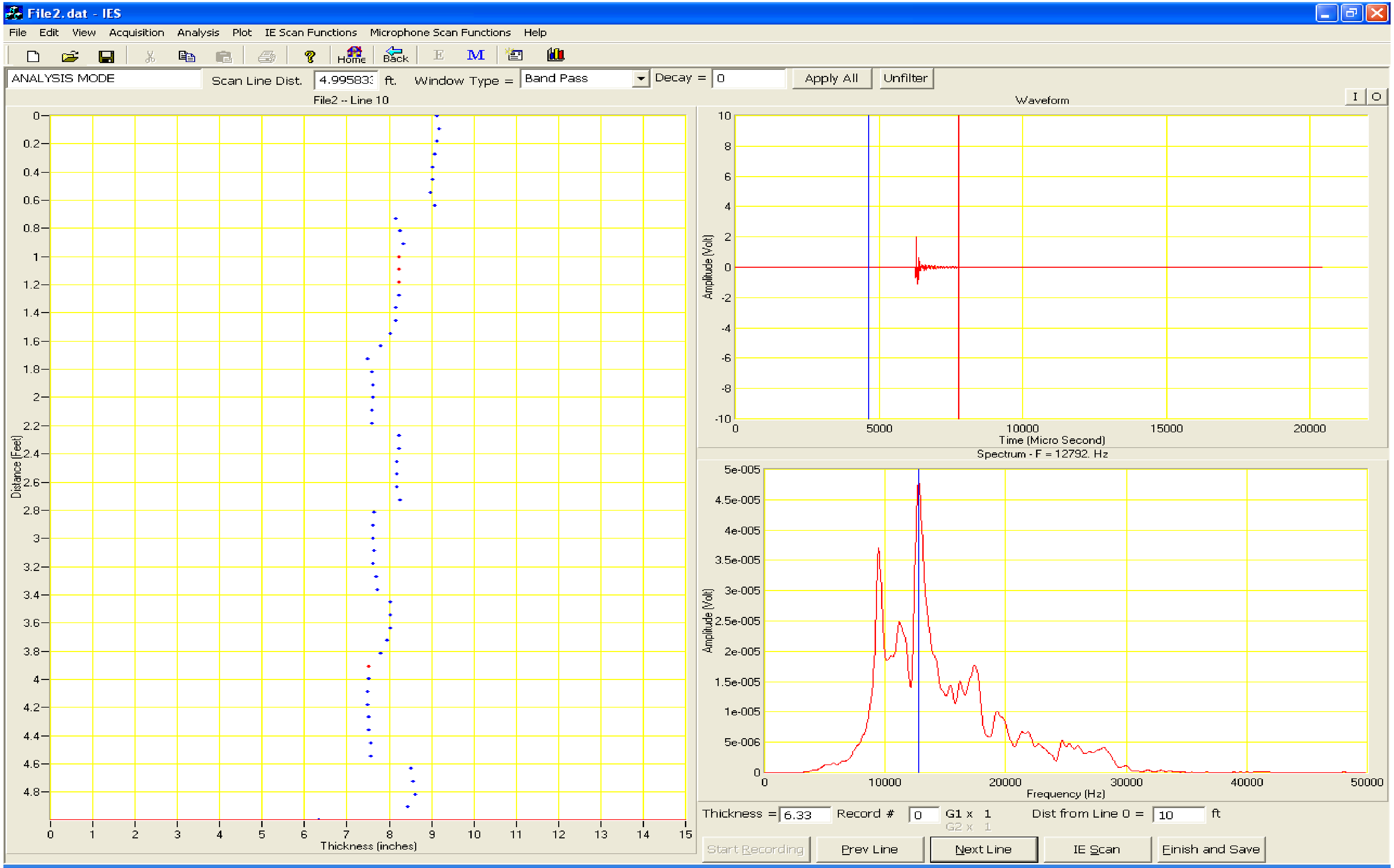


Typical 3-D IE Scan on Precast Box Girder – Ungrouted, Voided Ducts in Yard, 7.5 inch wall (scales in feet)

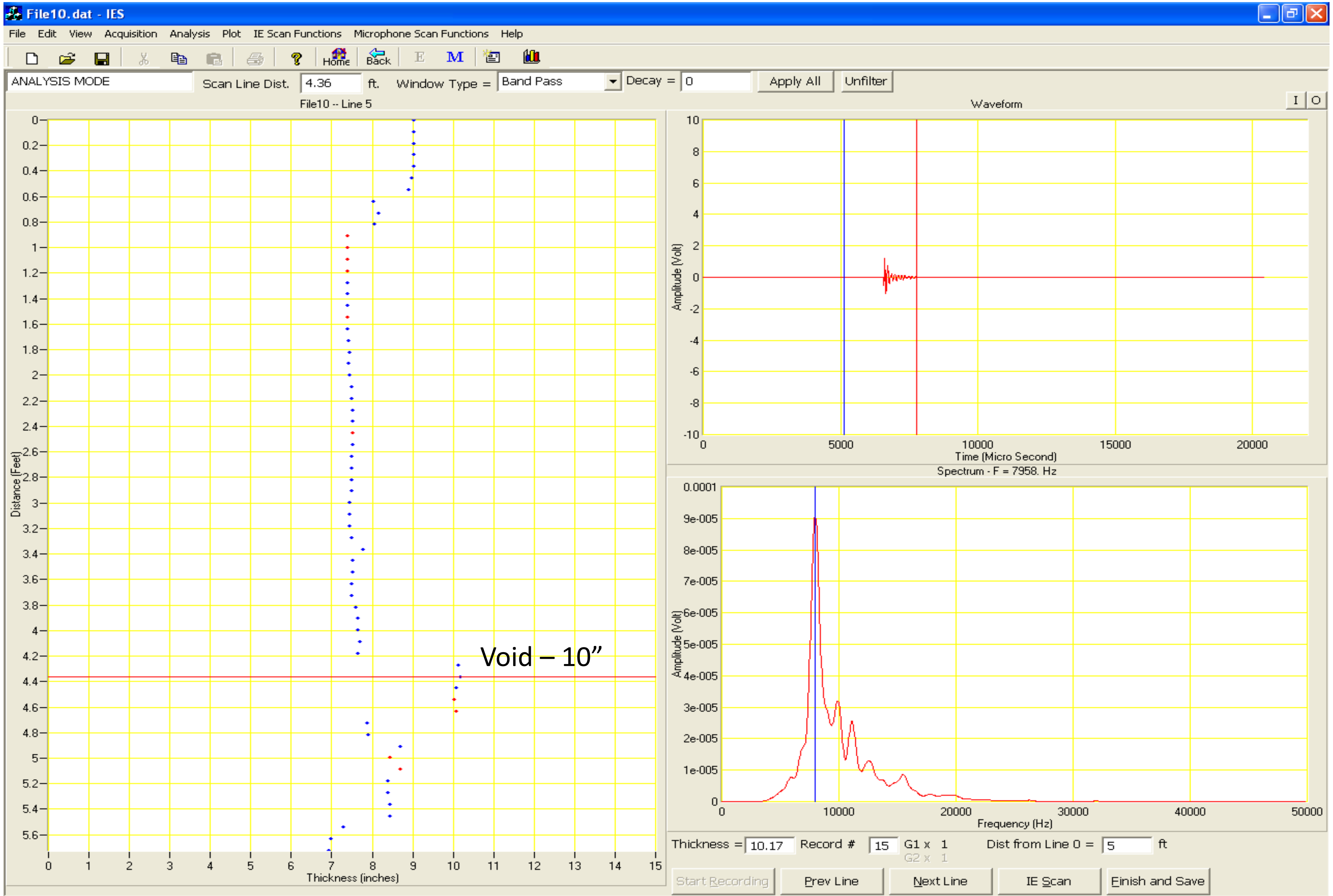


Impact Echo Scanning was conducted up the outside bridge web walls or the inside walls depending on access to the post-tensioned box girder bridge

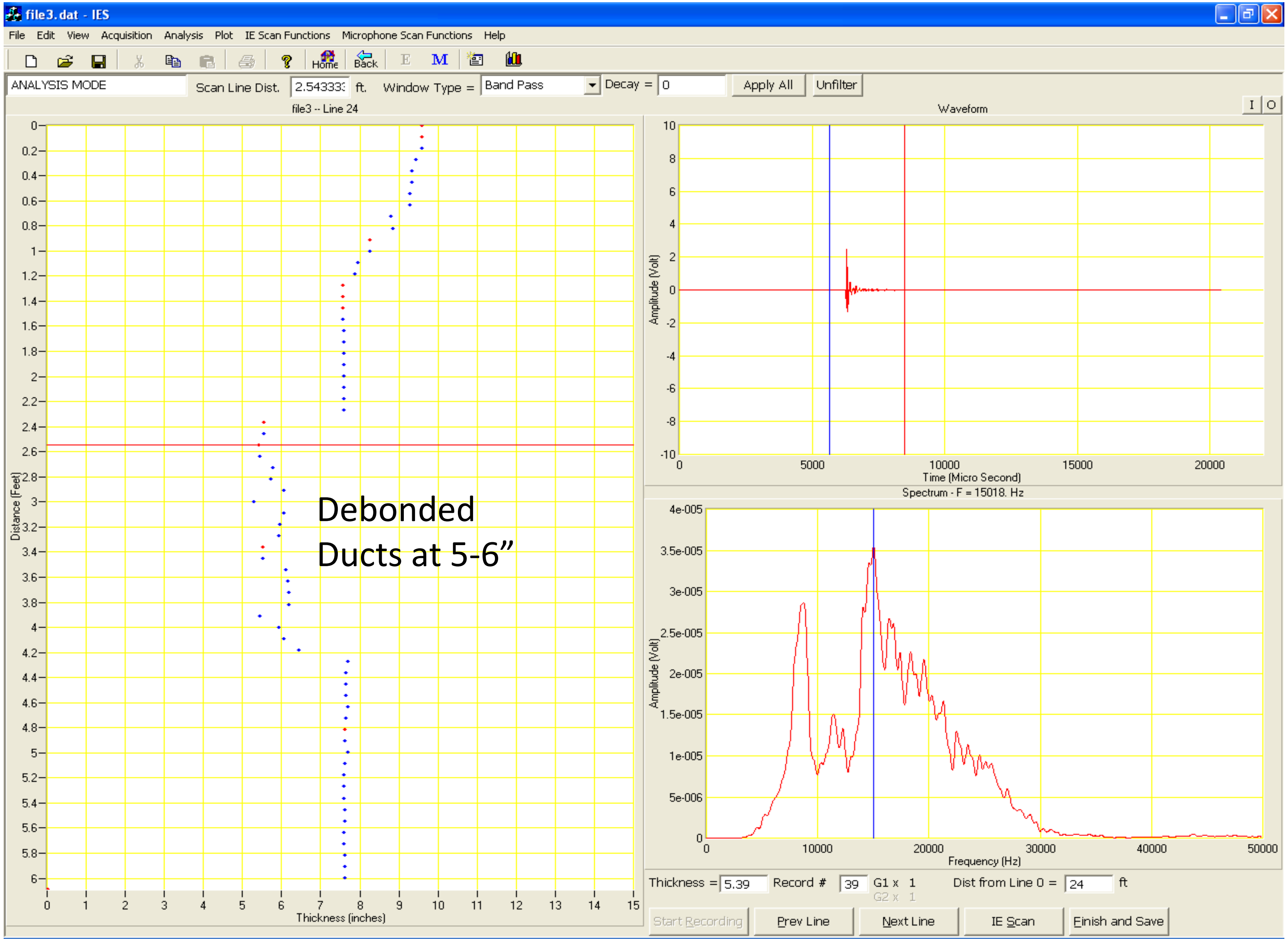
Girder 1R Left Side – Sound Impact Echo Scan



Girder 7L, Line 73, Right Side – T1 = Void (confirmed by drilling and borescope)



Girder 6R Line 60 Right – Thin Readings indicative of debonded ducts due to curved girder stressing of PT



Summary of Impact Echo Scanning of PT Bridge Ducts

- Over a dozen bridges tested to date
- Grout defects confirmed with borescope with good to very good agreement for PT ducts
- Voids filled with air and water
- Bridges tested with 1 to 2 rows of PT ducts
- Fully grouted plastic ducts can be detected and verified as being grouted even if the ducts are partially debonded
- Duct Voids grouted to fill voids and mitigate long-term risk of corrosion of tendons

Corrosion Detection in Reinforced Concrete Bridge Decks with NDE Methods

-Bridge Deck Scanner with Impact Echo
-Acoustic Sounding
-Ground Penetrating Radar

Sonic NDE with NCHRP IDEAS Research on Bridge Deck Scanner

- Part of the NCHRP IDEAS No. 132 research project to develop high speed non-destructive evaluation techniques for bridges

- Objectives
  - To detect top delaminations with accurate mapping
  - To identify internal conditions; including void/honeycomb, cracks, crack depth, concrete deterioration and bottom deck delamination mapping
  - To profile thickness
  - To measure stiffness/structural integrity of the deck

Nondestructive Testing Methods in the Bridge Deck Scanner (BDS)

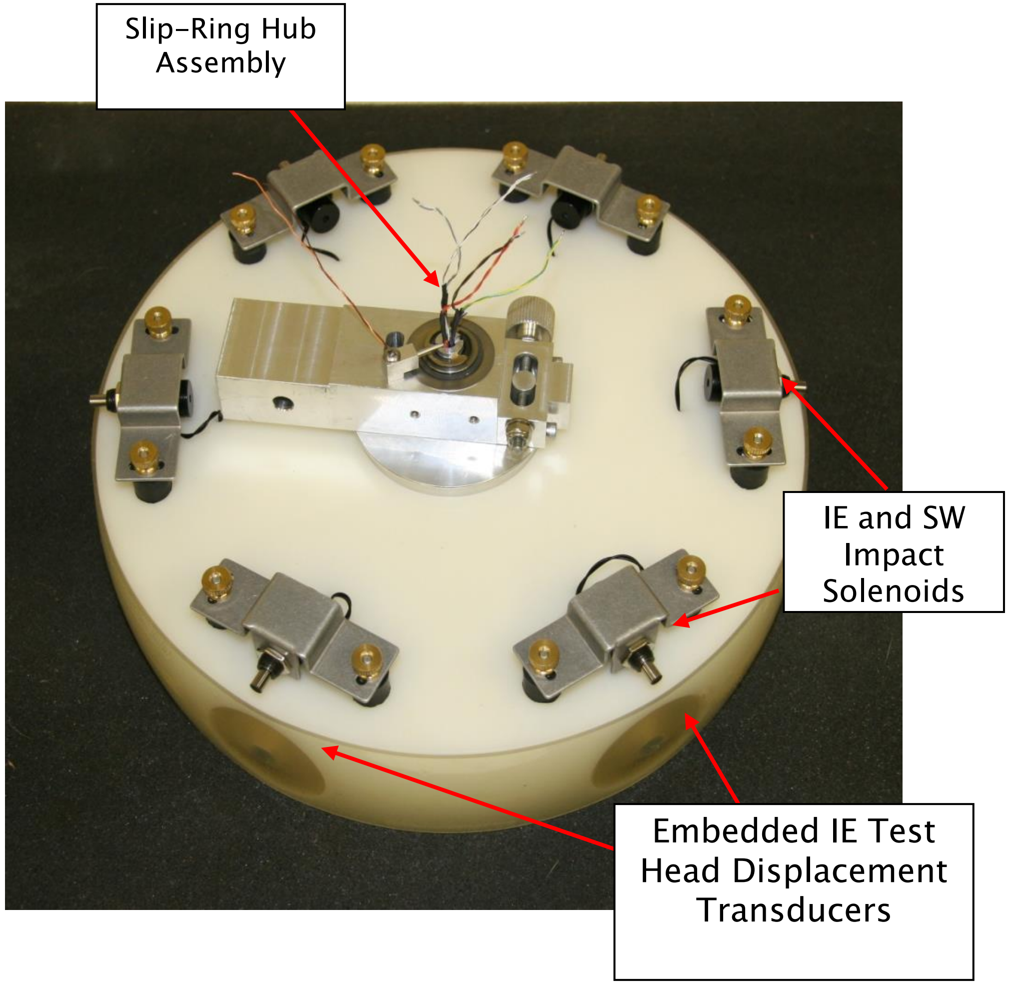
- Impact Echo (IE)
- Spectral Analysis of Surface Waves (SASW)

Vehicle Mounted Bridge Deck Scanner Concept

- Connect/disconnect easily to a hitch of any vehicle
- Perform several NDT tests simultaneously
- Easy to operate with driver and engineer
- Slow Rolling at ~ 1 to 1.5 mph
- Tests every 6 inches with 2 scanning wheels spaced 1 ft apart
- Olson Instruments Freedom Data PC for data acquisition

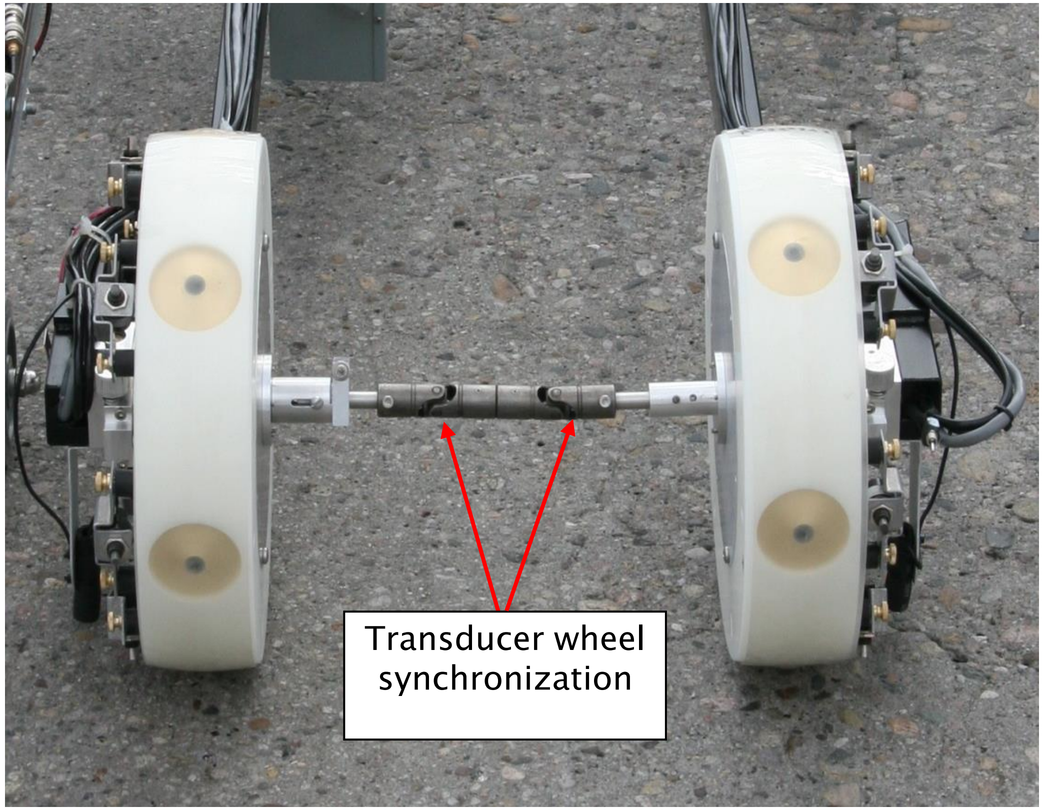
Scanning Impact Echo Testing

- Diameter of Wheel = 11.5 inches
- Six individual displacement transducers
- Six individual impactors
- Space 6 inches apart along a scan line (around the wheel circumference)
- The 6 transducers were spring mounted with rubber isolators and captured with a thin (1/16”) urethane tire approximately 2.5” wide
- The thin urethane tire was added as a dust cover and to improve coupling

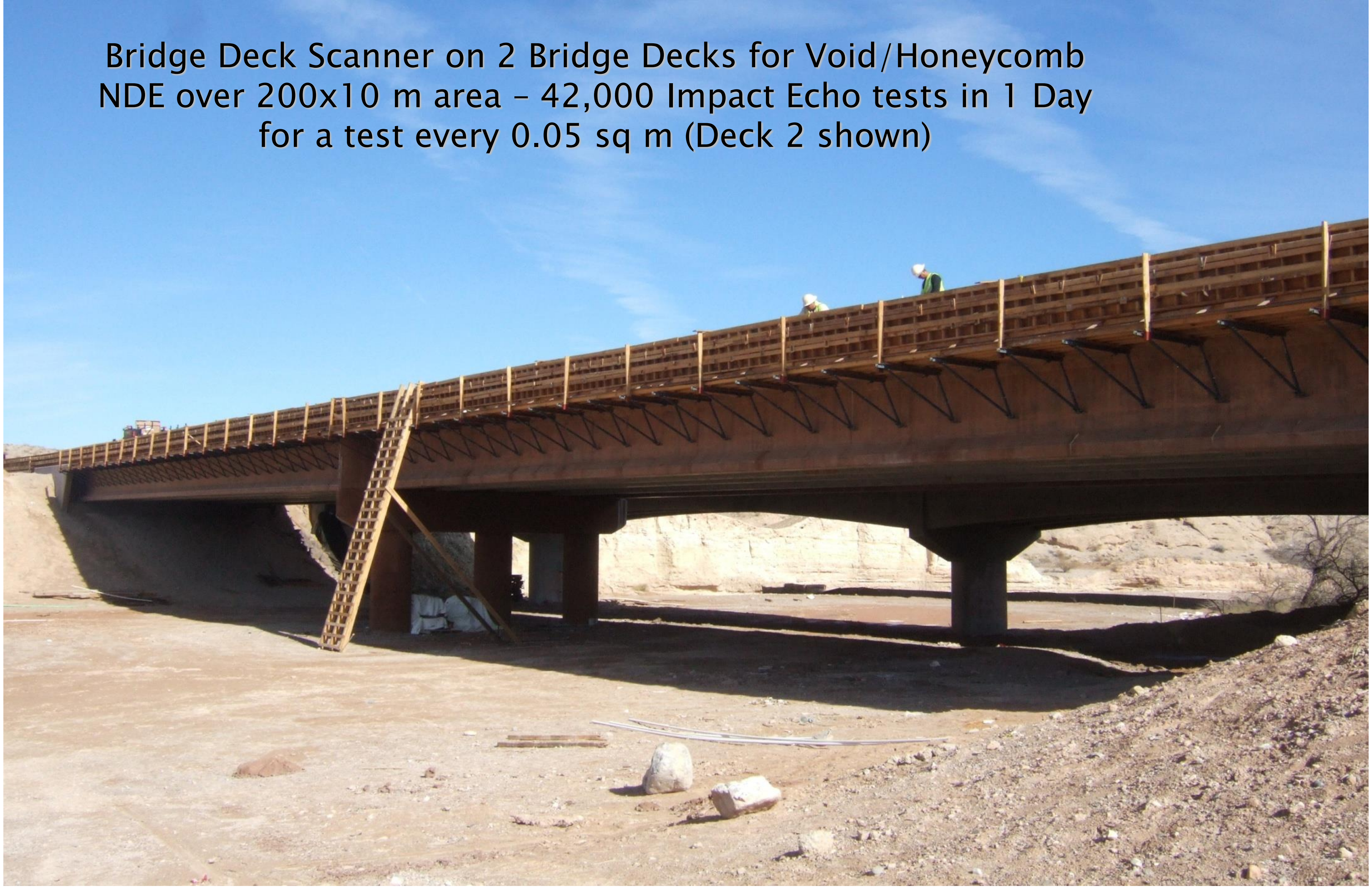


Scanning Impact Echo/Spectral Analysis of Surface Waves

- Use 2 identical sensor/impactor wheels
- Only one wheel with the impactor turned on
- The spacing between the transducers is 1 foot
- Can rotate the wheels 30 degree out of phase to perform IE testing on both wheels simultaneously

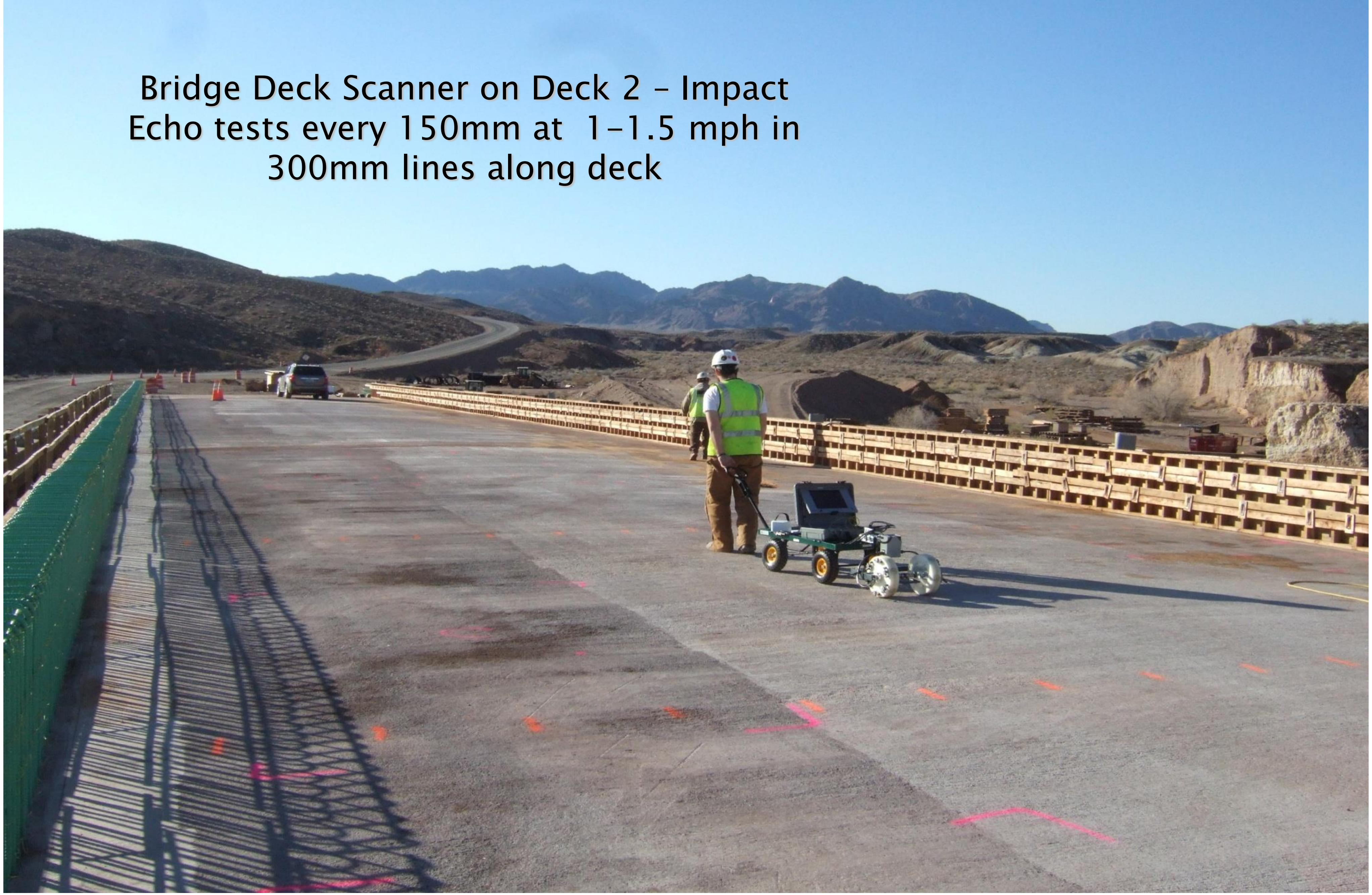


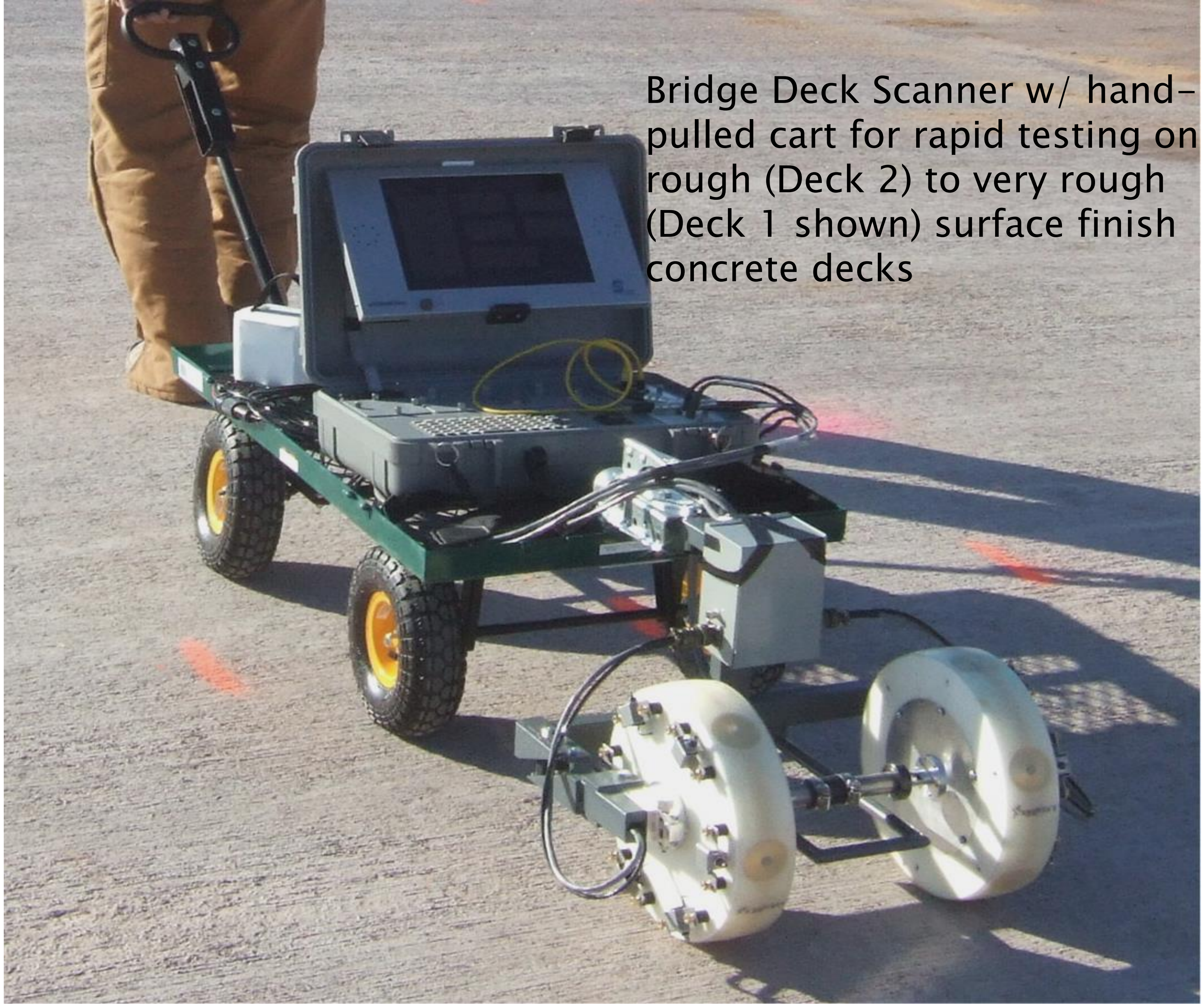
Bridge Deck Scanner on 2 Bridge Decks for Void/Honeycomb NDE over 200x10 m area – 42,000 Impact Echo tests in 1 Day for a test every 0.05 sq m (Deck 2 shown)



Bridge Deck Scanner Tests on Grid Lines at 300mm across width of decks with cart – Deck 1


Bridge Deck Scanner Impact
Echo Tests detected
Bridge 2 Piers

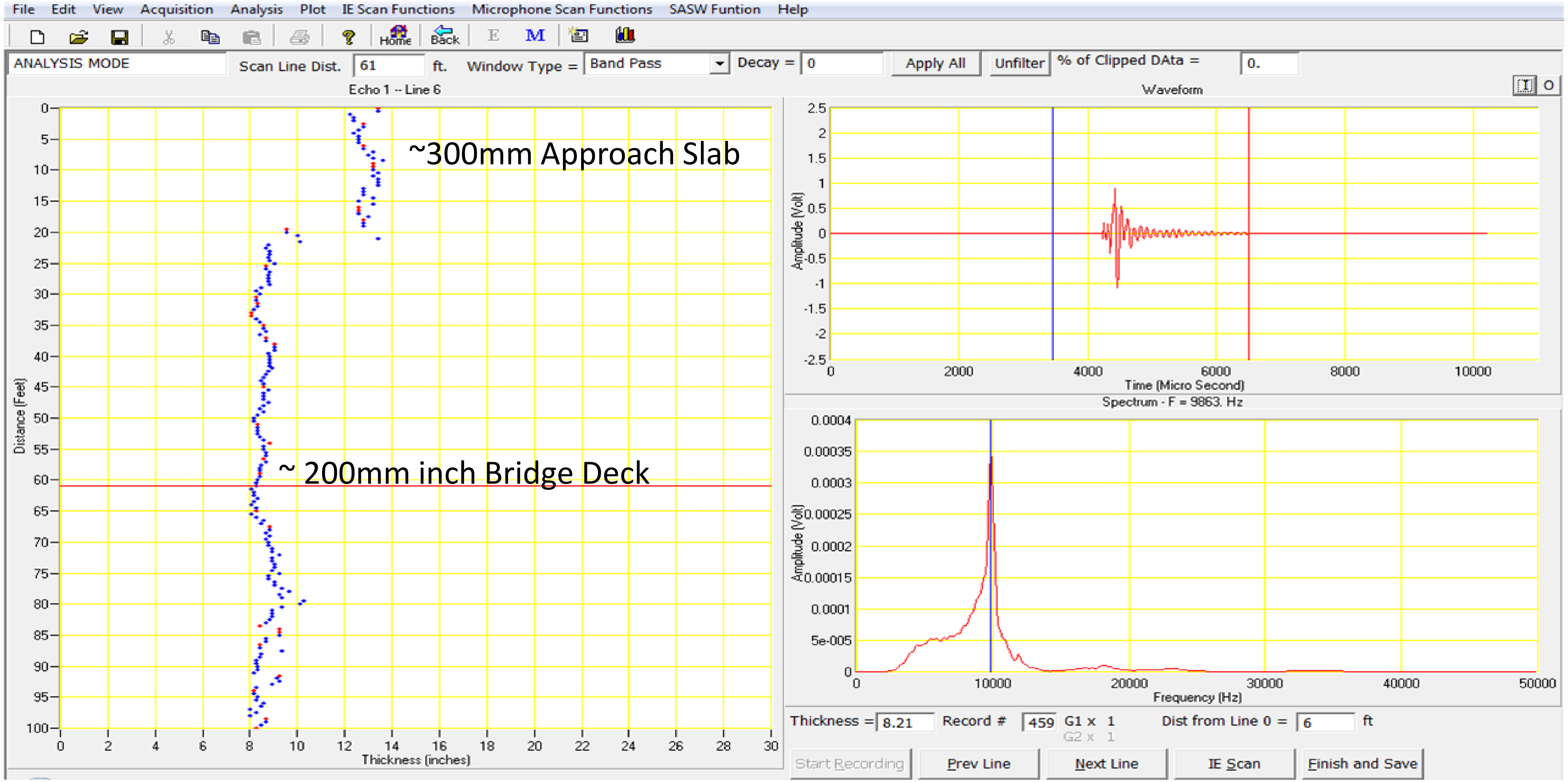

Bridge Deck Scanner on Deck 2 – Impact
Echo tests every 150mm at 1-1.5 mph in
300mm lines along deck



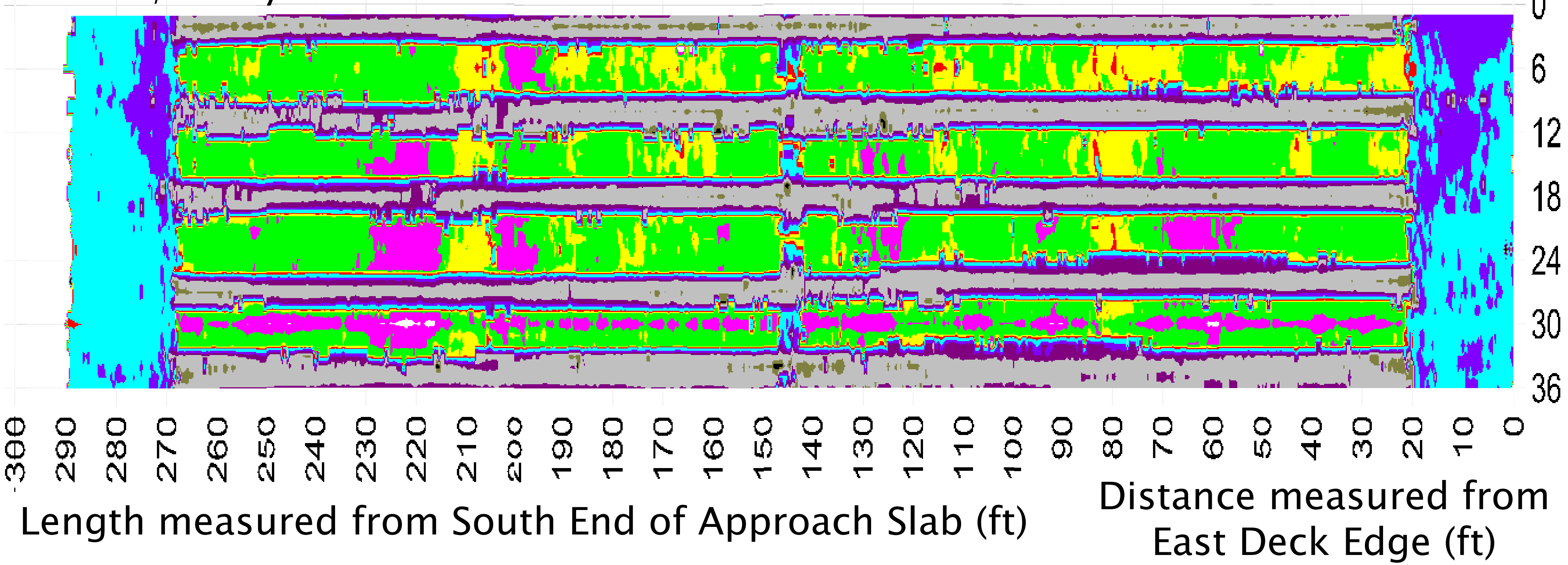
Bridge Deck Scanner w/ hand-pulled cart for rapid testing on rough (Deck 2) to very rough (Deck 1 shown) surface finish concrete decks

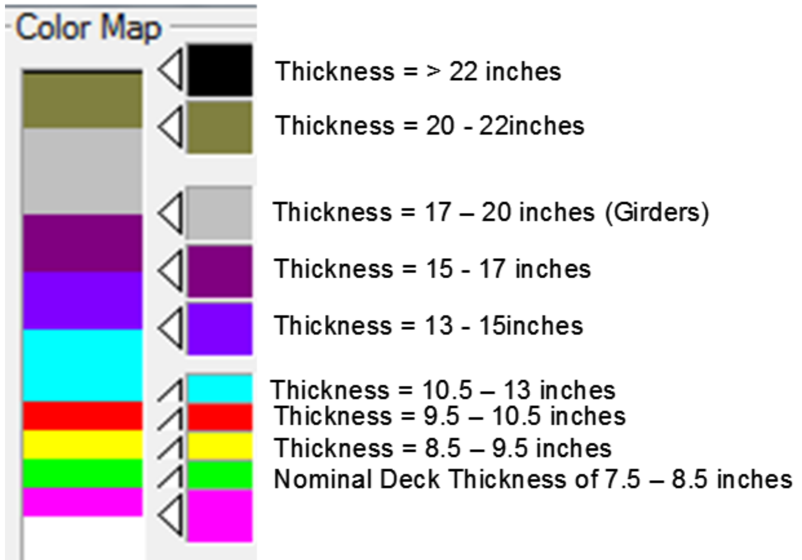
BDS Impact Echo Thickness Plot vs. 30m Distance for a scan line along Deck 2

Time Domain IE Signal at left cursor (Top Plot) and Frequency Domain Echo Depth Resonance Depth=Velocity/(2 x echo frequency)=205mm inches (Bottom Plot)

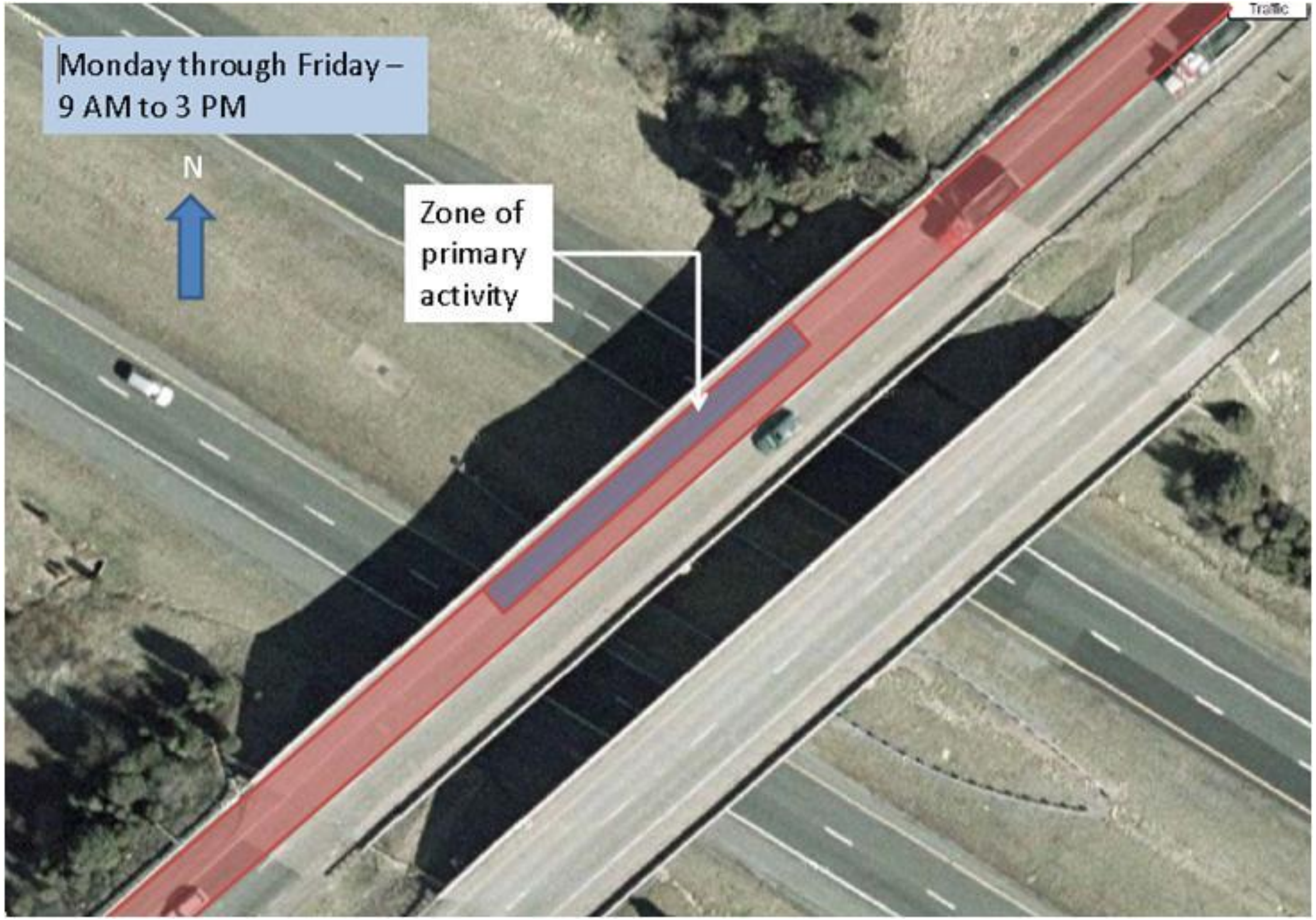


Deck 2 BDS Impact Echo Dominant Echo Thickness Results No significant void/honeycomb found – Green is Deck Echo



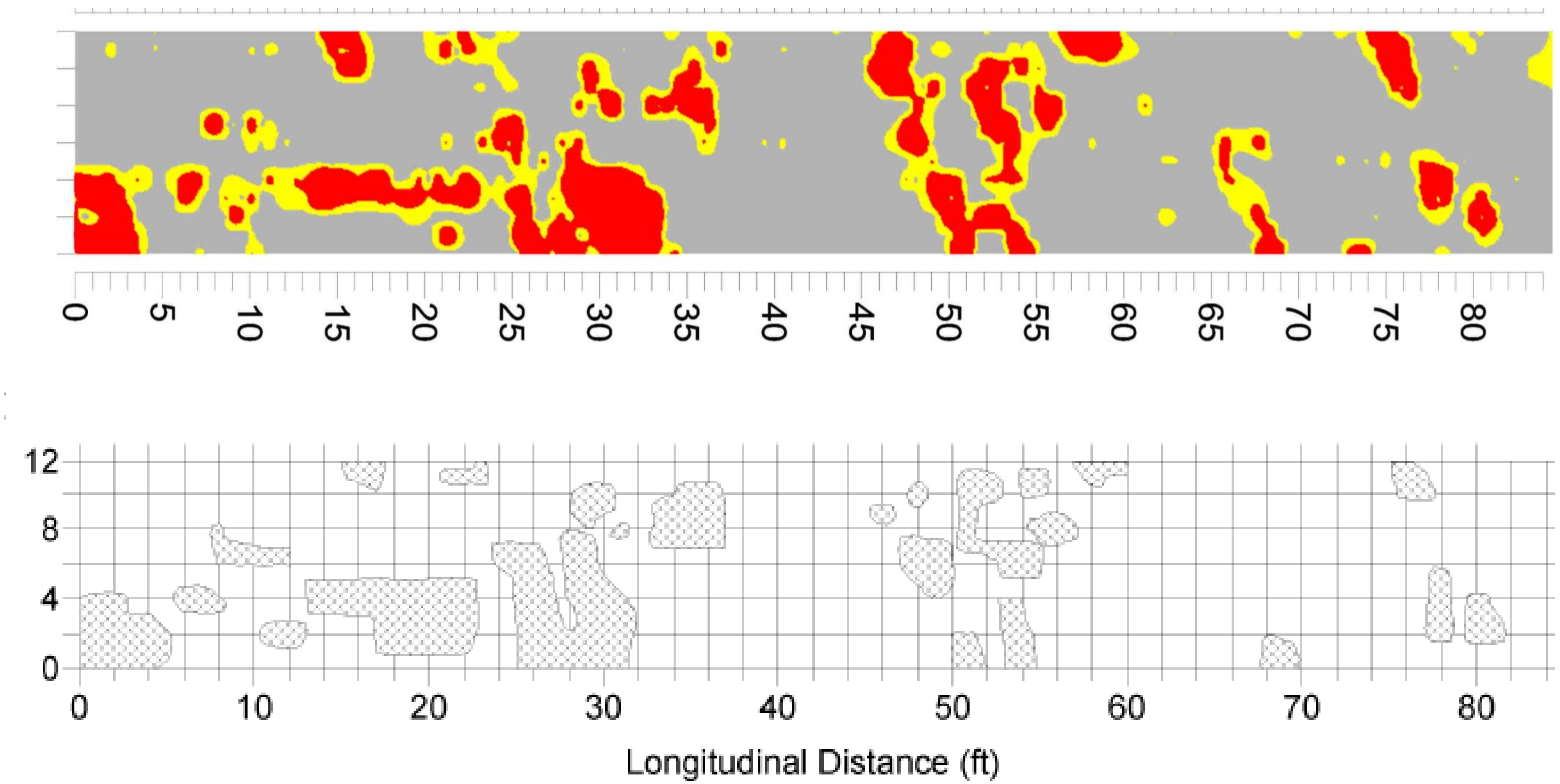


Case Study # 3 – Virginia Bridge Deck, James Madison US Highway 15

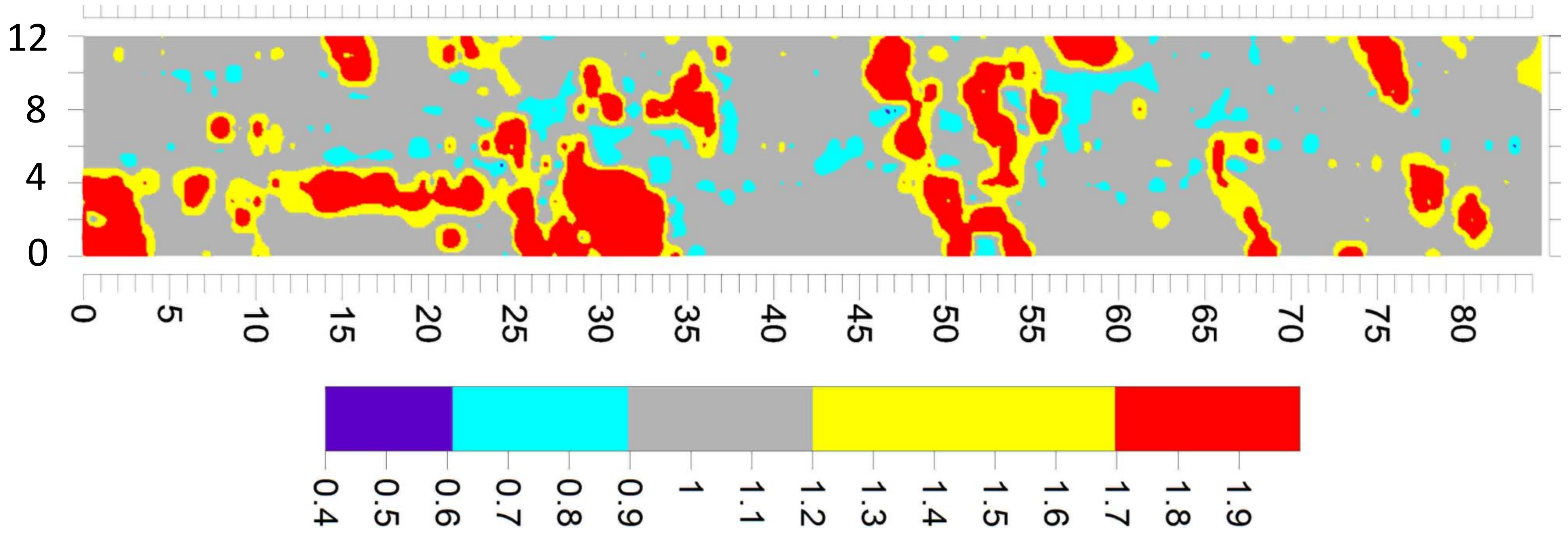


Strategic Highway Research Program SHRP 2 Research R06D
by Dr. Nenad Gucunski of Rutgers University

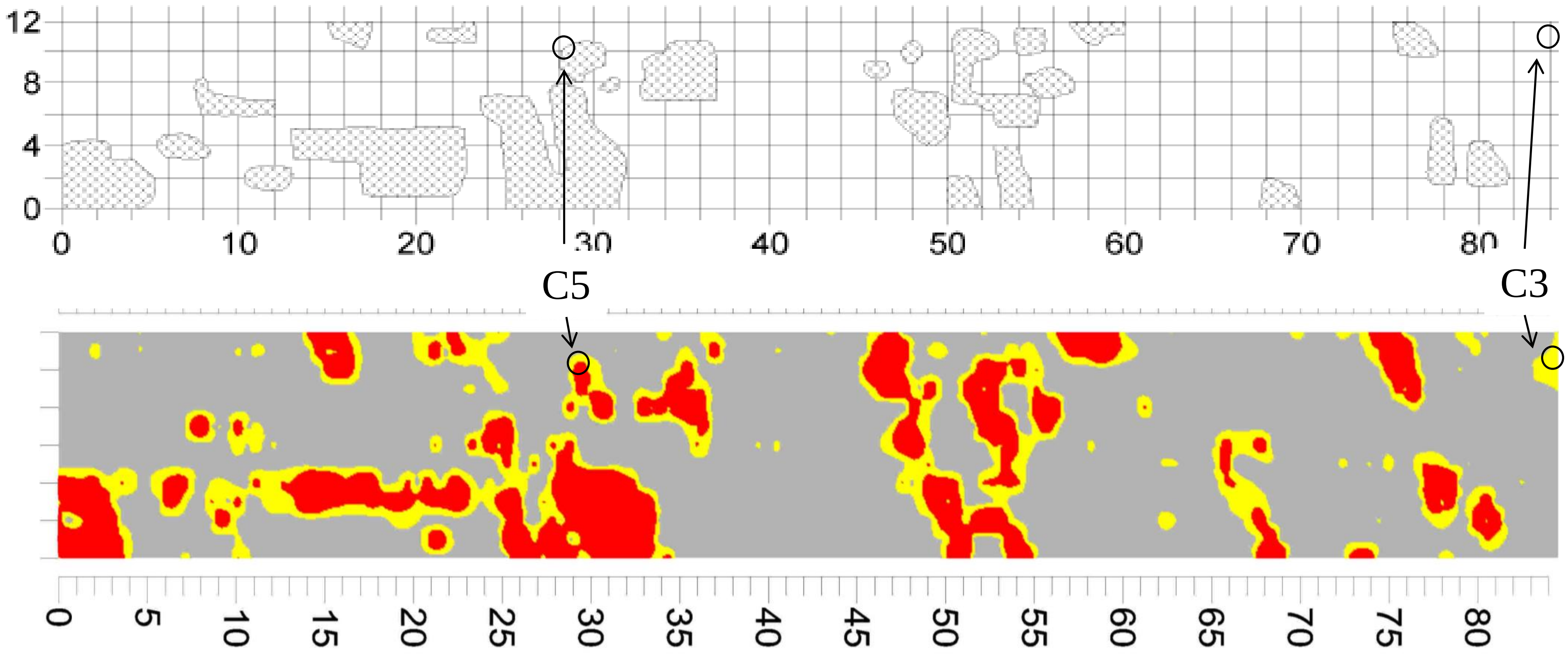
Top Delamination Test Results from the Impact Echo Scanning and Rutgers Chain Dragging



Impact Echo Test Results VA Deck – Full Deck Depth Results



Areas with Probable Top Delaminations = 14%
Areas with Probably Incipient Top Delaminations = 13%
Areas with Probable Bottom Delaminations (or Thin Section) = 5.7%

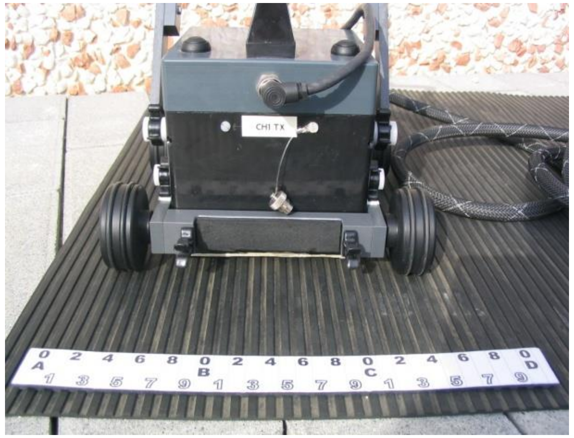


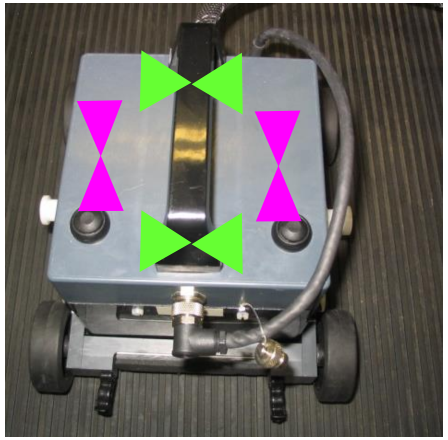
Comparisons between IE Test Results and Cores

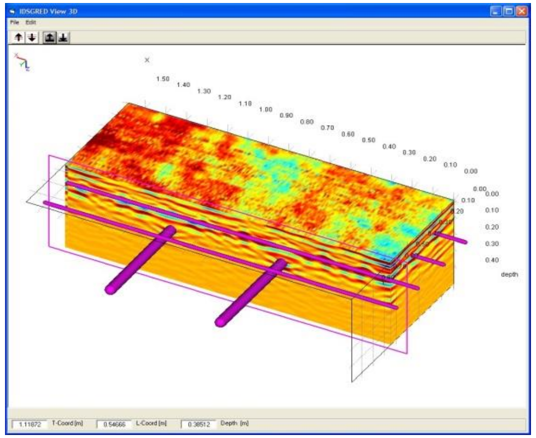
C5 – delamination at 2.5 inches

C3 – delamination at 3.5 inches

IDS Georadar – Aladdin GPR







1
OPERATIONAL CASE

2
PSG: INNOVATIVE SURVEY KIT-
THE “MAGIC GROOVED CARPET

3
FULL POLAR ANTENNA-
UP TO 4 COMBINATIONS

4
3D SOFTWARE FOR ON-SITE
PROCESSING FOR REBAR IMAGES

1. DEDICATED TRANSPORT/OPERATIONAL CASE

2. PSG: INNOVATIVE SURVEY KIT FOR AN EASY AND TOTAL 3D ACQUISITION DATA WITH GROOVED RUBBER CARPET

3. FULL POLAR ANTENNA (2 GHz): IMPROVES THE IMAGING OF SHALLOW AND DEEP REINFORCING BARS FOR REBAR MATS AND ANGLED BARS

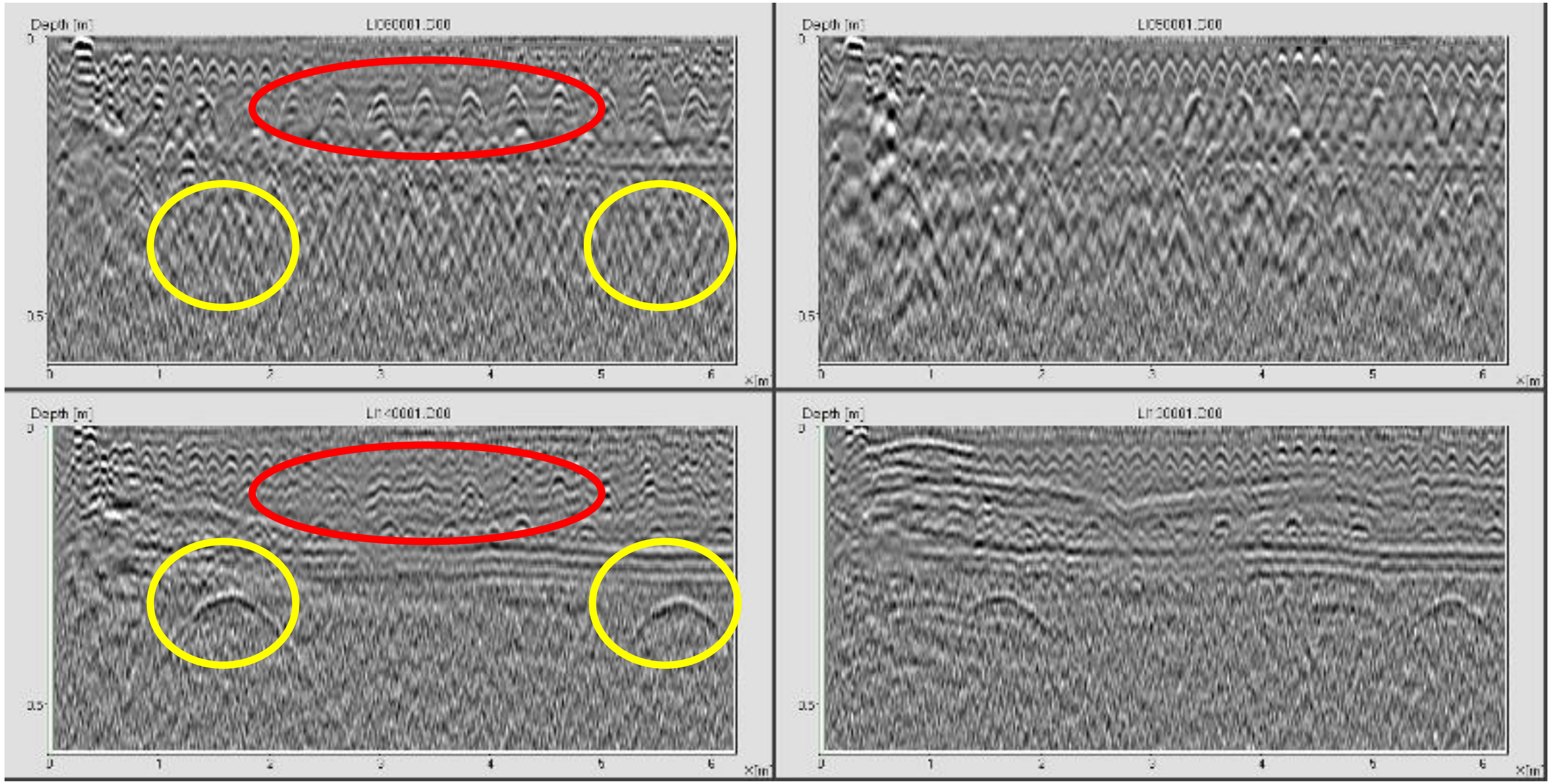
4. QUICK ON-SITE DATA PROCESSING

Benefit 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**

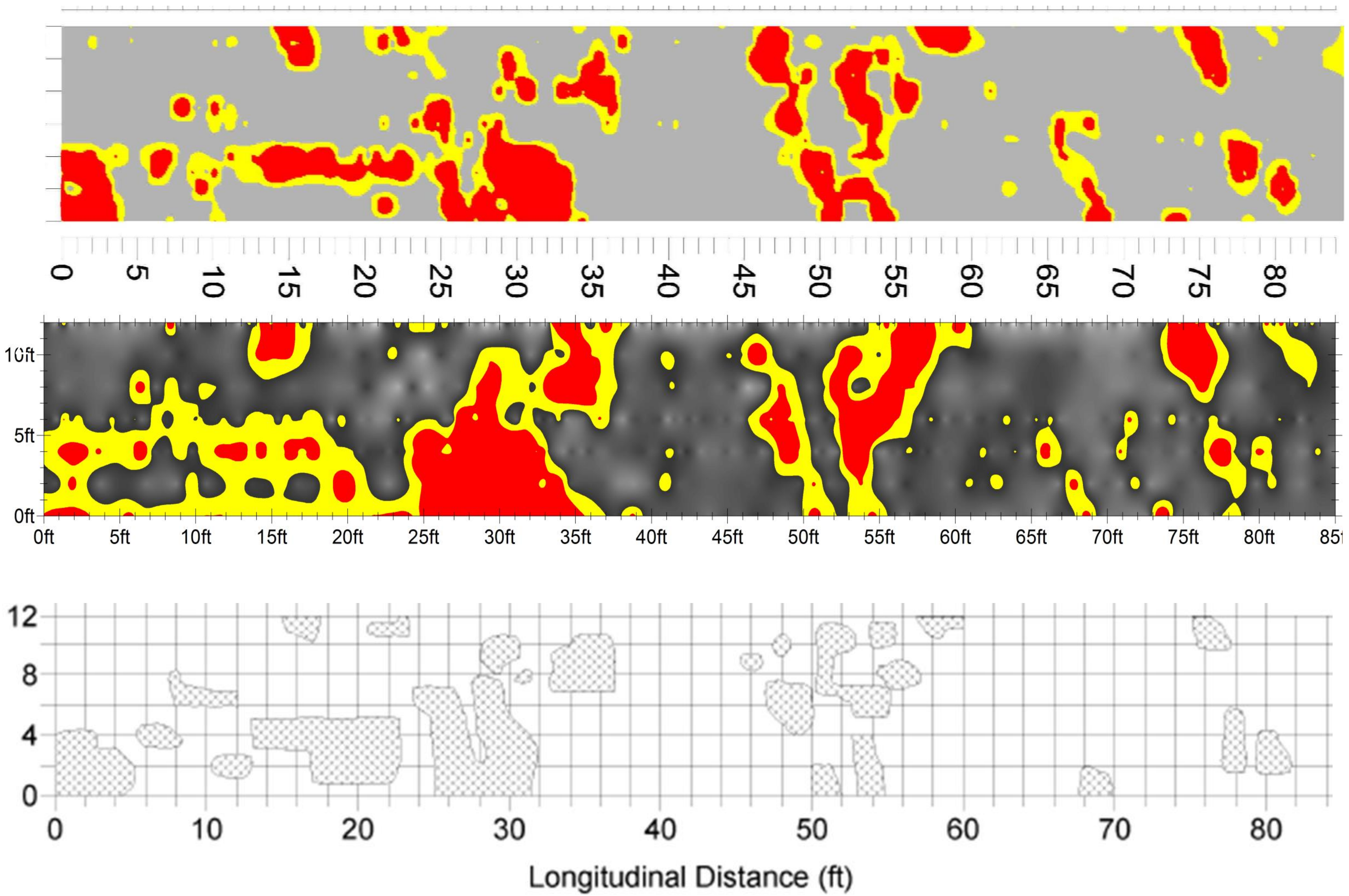
HH channels

VV channels



Aladdin 2 GHz GPR System Deck Scanning with Hand-Held and Cart Scanning

Top Delamination - Impact Echo (top), GPR (middle), Chain Drag (bottom)



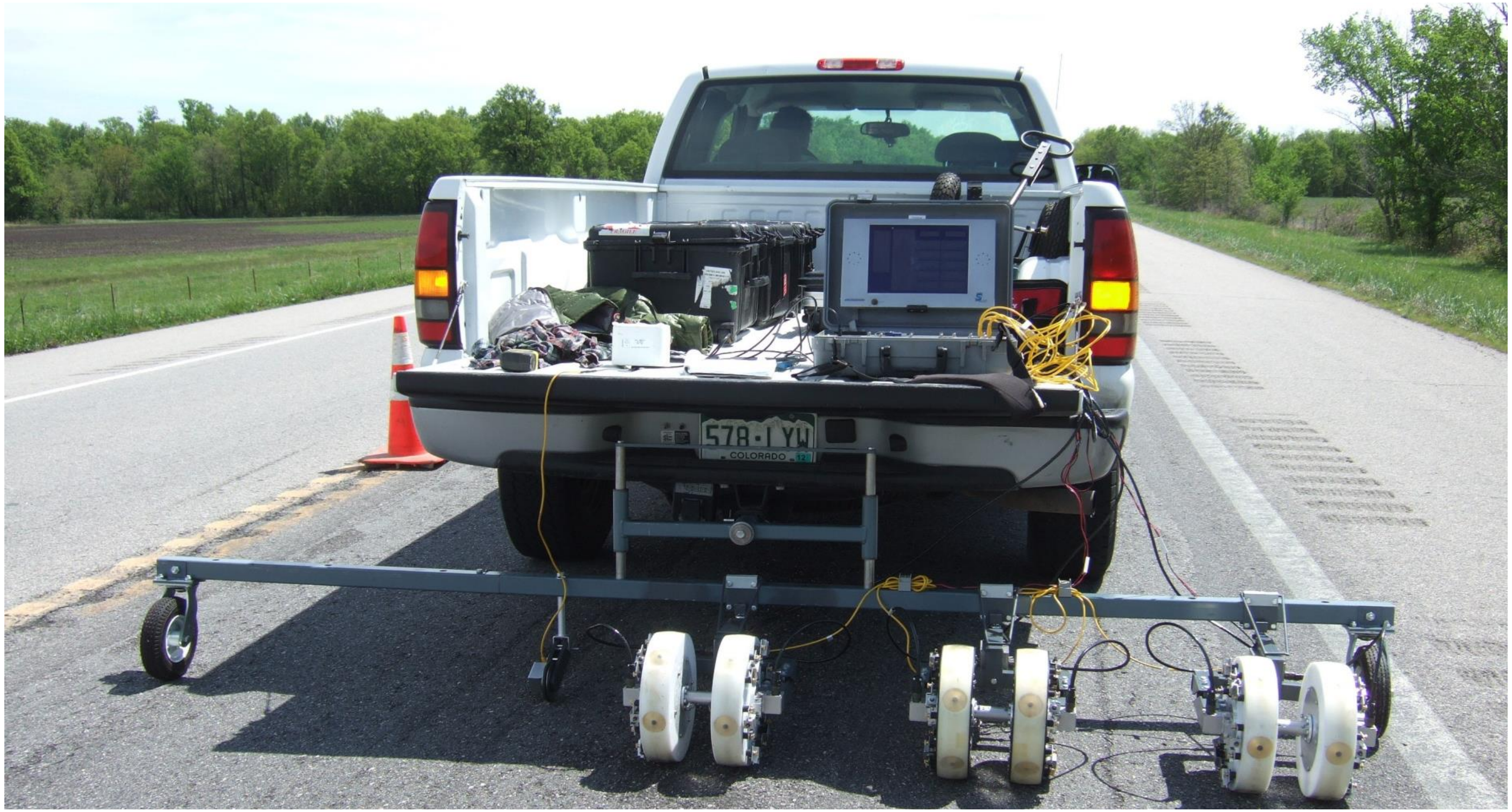
Bridge Deck Scanner Summary

- **Impact Echo Scanning had the most resolution of Top Delaminations on concrete bridges**

- **IE identified bottom delaminations as well as profiling deck thickness echoes. GPR method is not sensitive to bottom delaminations**

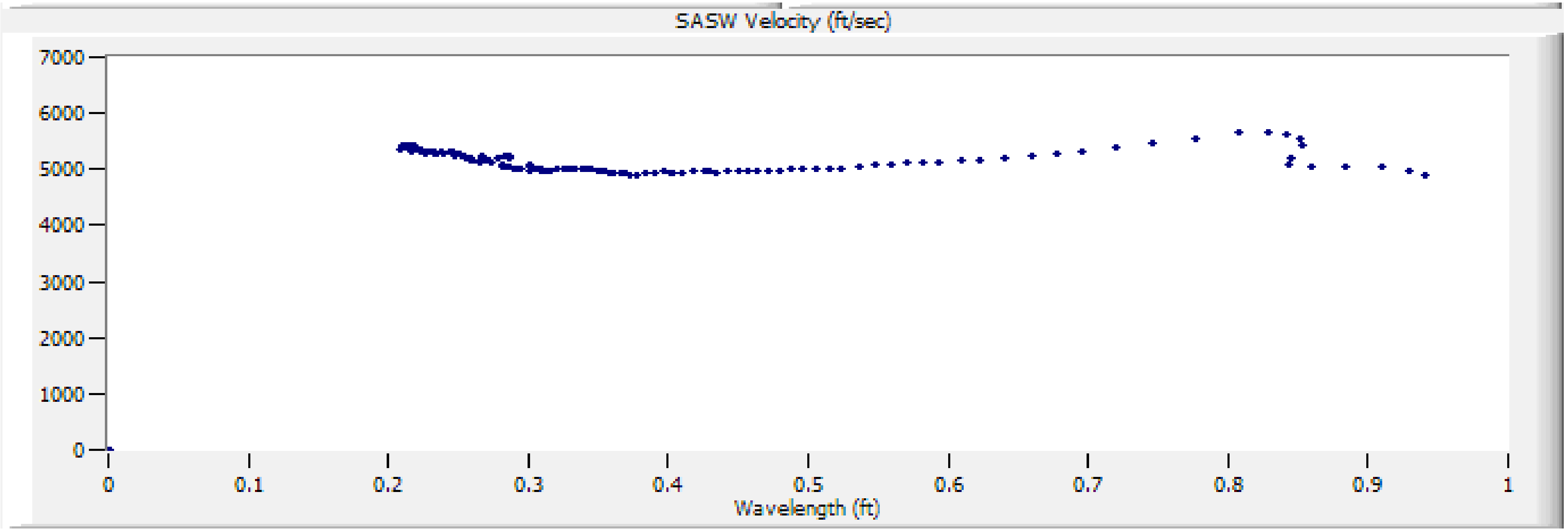
- **Spectral Analysis of Surface Waves (SASW) for cracking damage due to freeze-thaw, Alkali-Silica/Aggregate Reactions, general condition assessment**

SHRP R06(D) Research on Stress Wave Detection of Delaminations within Asphalt Pavements, Three project sites: National Center for Asphalt Technologies at Auburn University in Alabama, Florida and Kansas



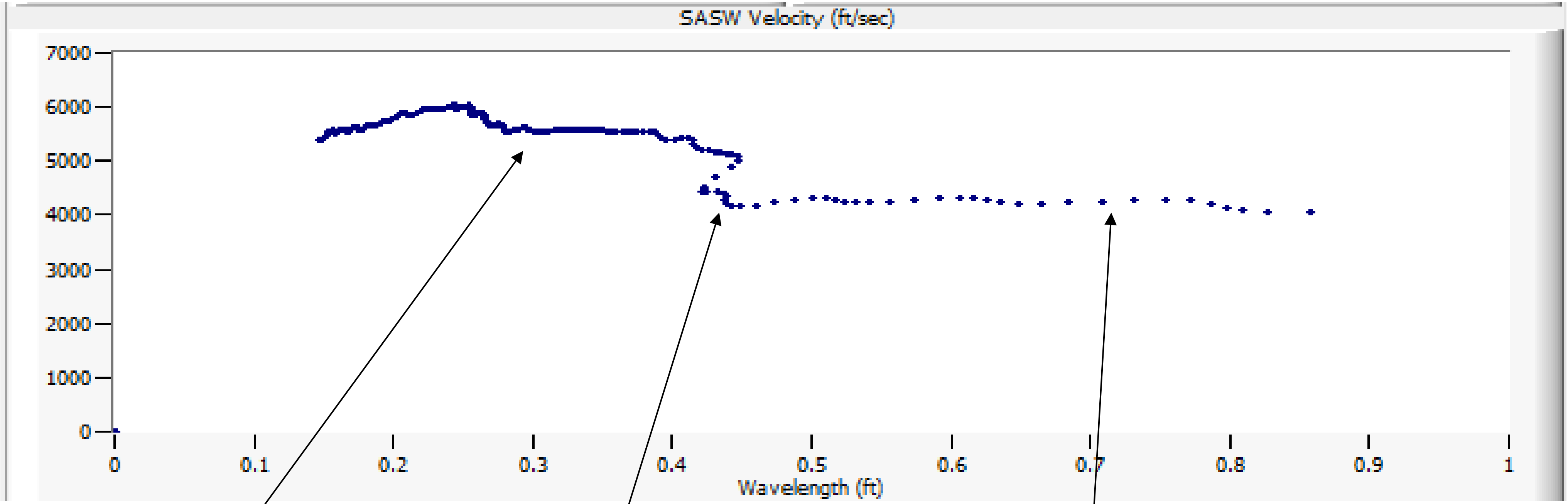
Pavement Scanner on Kansas Asphalt Pavement site with 3 pairs of wheels spaced 150 mm (0.5 ft) apart for combined Impact Echo and Spectral Analysis of Surface Waves scanning.

Example SASW Dispersion Curve from Sound HMA Asphalt Pavement on Concrete Pavement



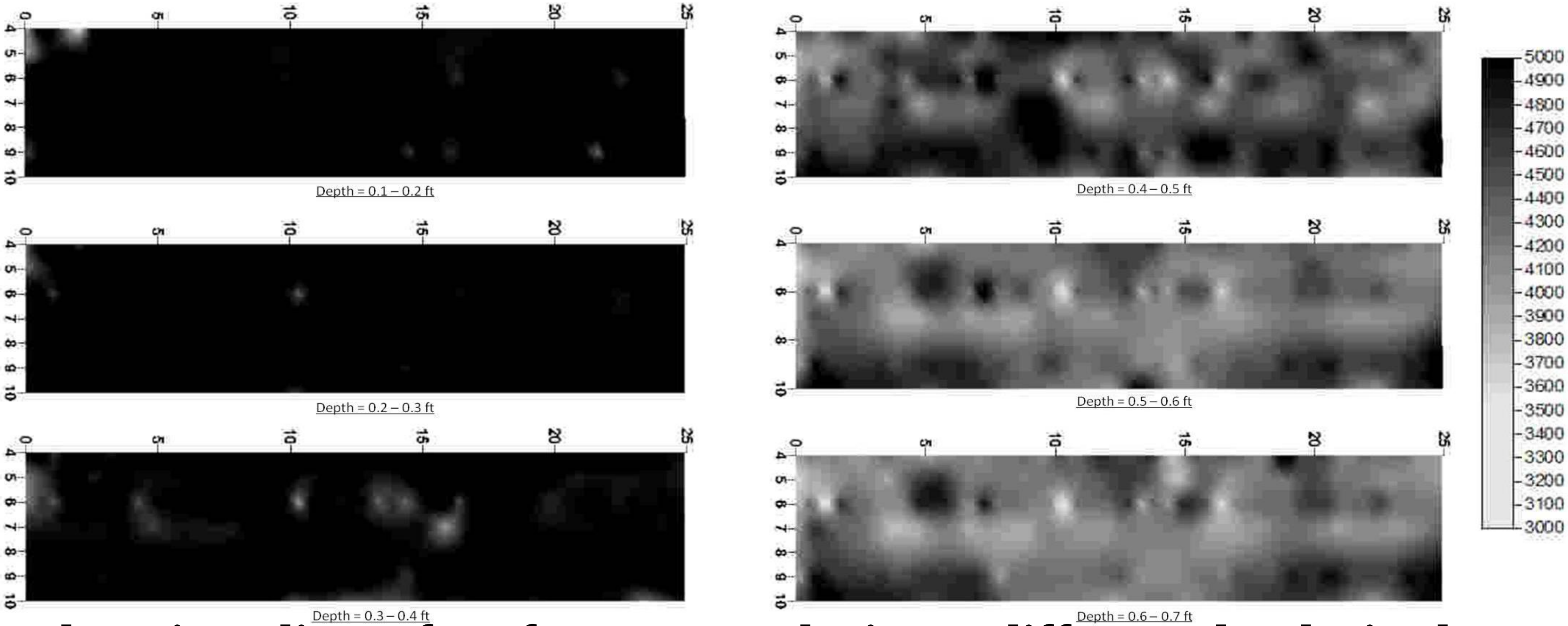
Sound, well-bonded asphalt lifts to about 10 inches (250 mm) deep – note surface wave velocity decrease from ~1560 m/s (5200 ft/s on vertical scale) to a wavelength of 0.83 ft (~10 inches or 250 mm on horizontal scale)

Example SASW Dispersion Curves from 12.5 cm (5 inch) deep Thin Paper Delamination Condition on Asphalt Pavement



Delamination due to Thin Paper Delamination built at 12.5 cm (5 inches) deep – note surface wave velocity decrease from ~1590 m/s (~5300 ft/s on vertical scale) to ~1290 m/s (~4300 ft/s) at a wavelength of 12.5 cm (0.43 ft - ~ 5 inches)

Example SASW Dispersion Curves from depths of 0 to 18 cm (0 to 7 inches) - Delamination Conditions on Asphalt Pavement noted by light gray to white



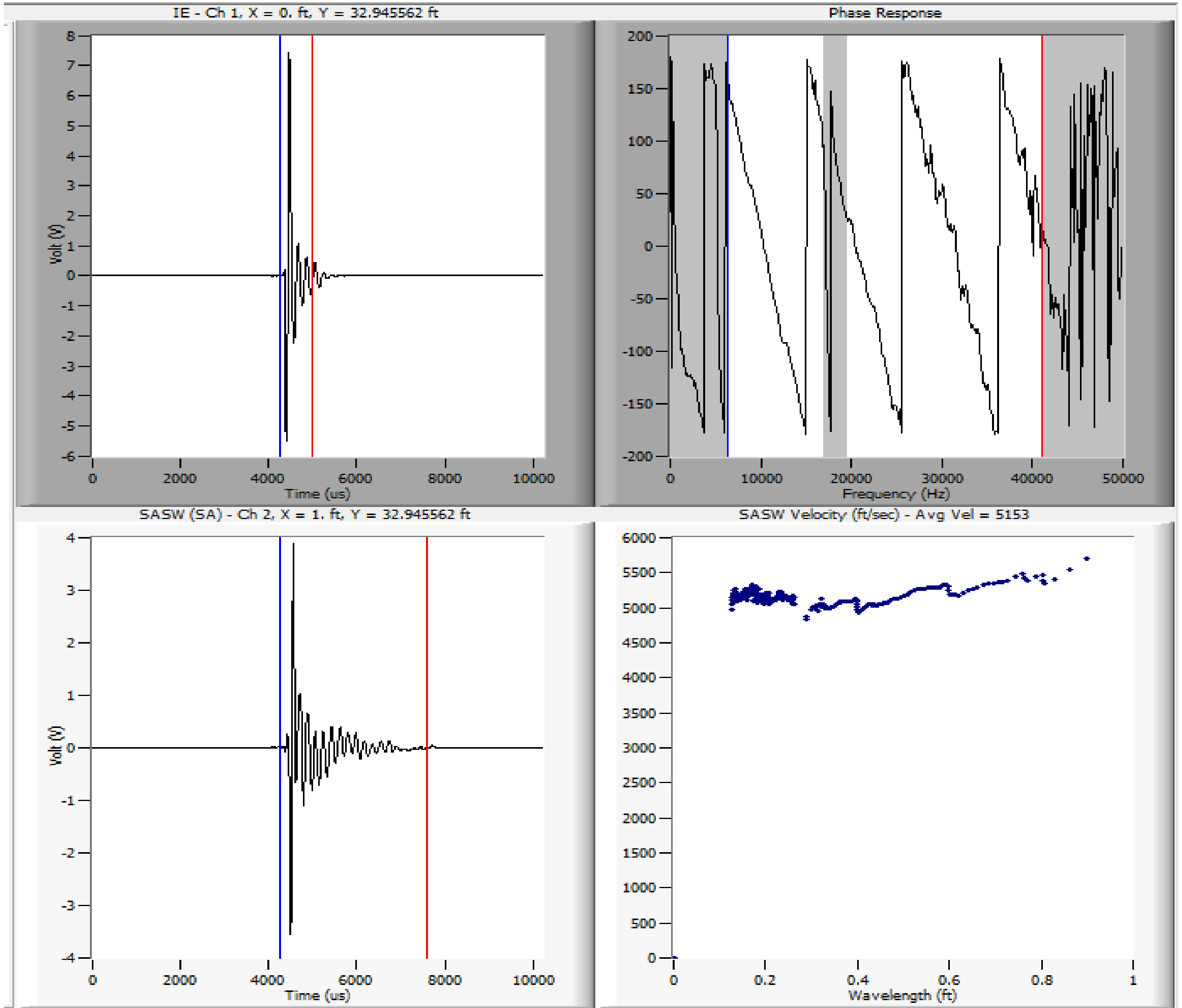
Plan view slices of surface wave velocity at different depths in the pavement showing a significant drop in velocity at a depth of 12-15 cm (0.4-0.5 ft) which correspond to delaminations

Internal Research Project on 2 Asphalt Overlaid Decks with the Colorado DOT using BDS with Surface Waves and Impact Echo

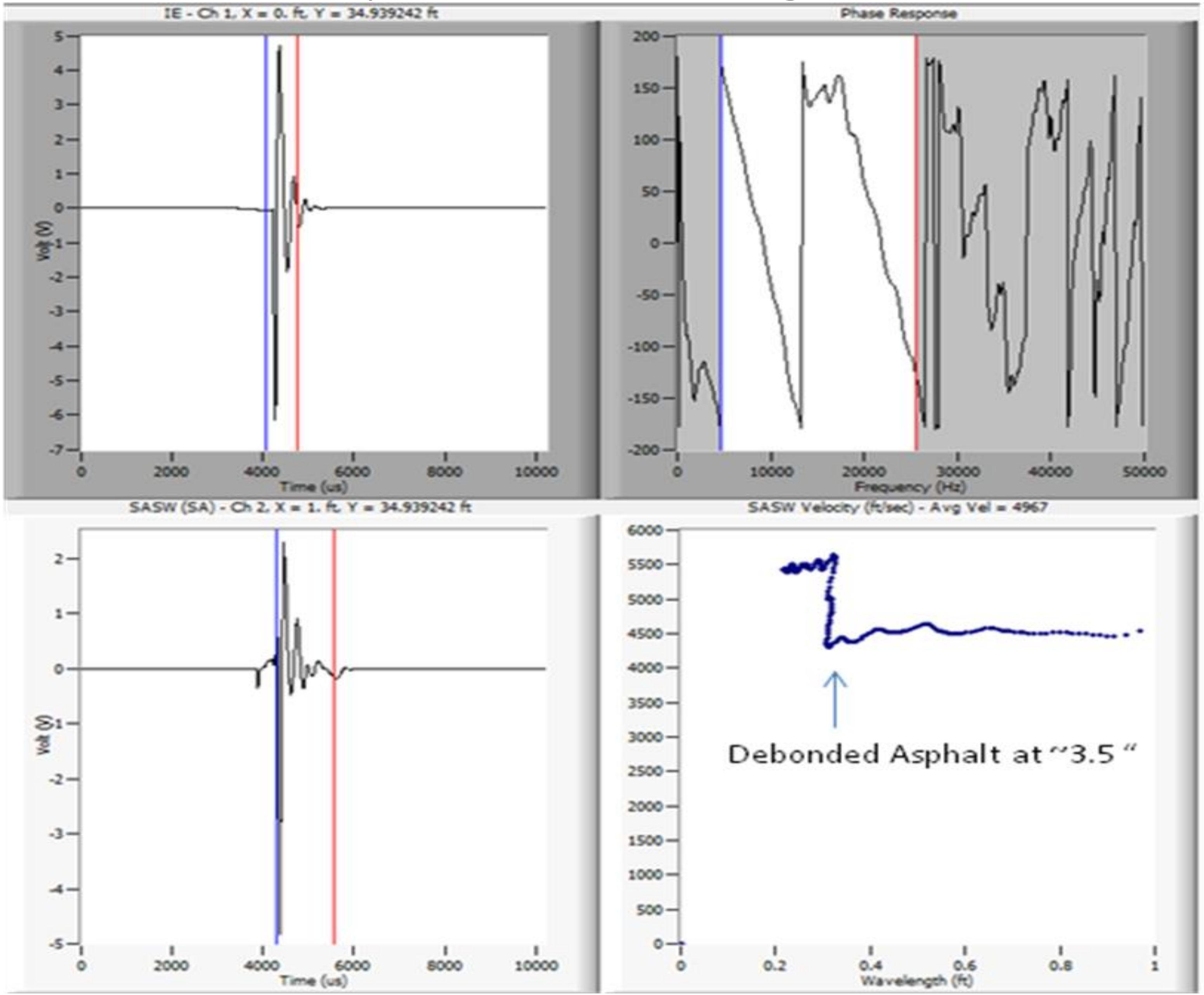
- Structure E-17-IN: I-270 westbound bridge over Dahlia Street (asphalt covered concrete deck with water-proofing membrane)

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

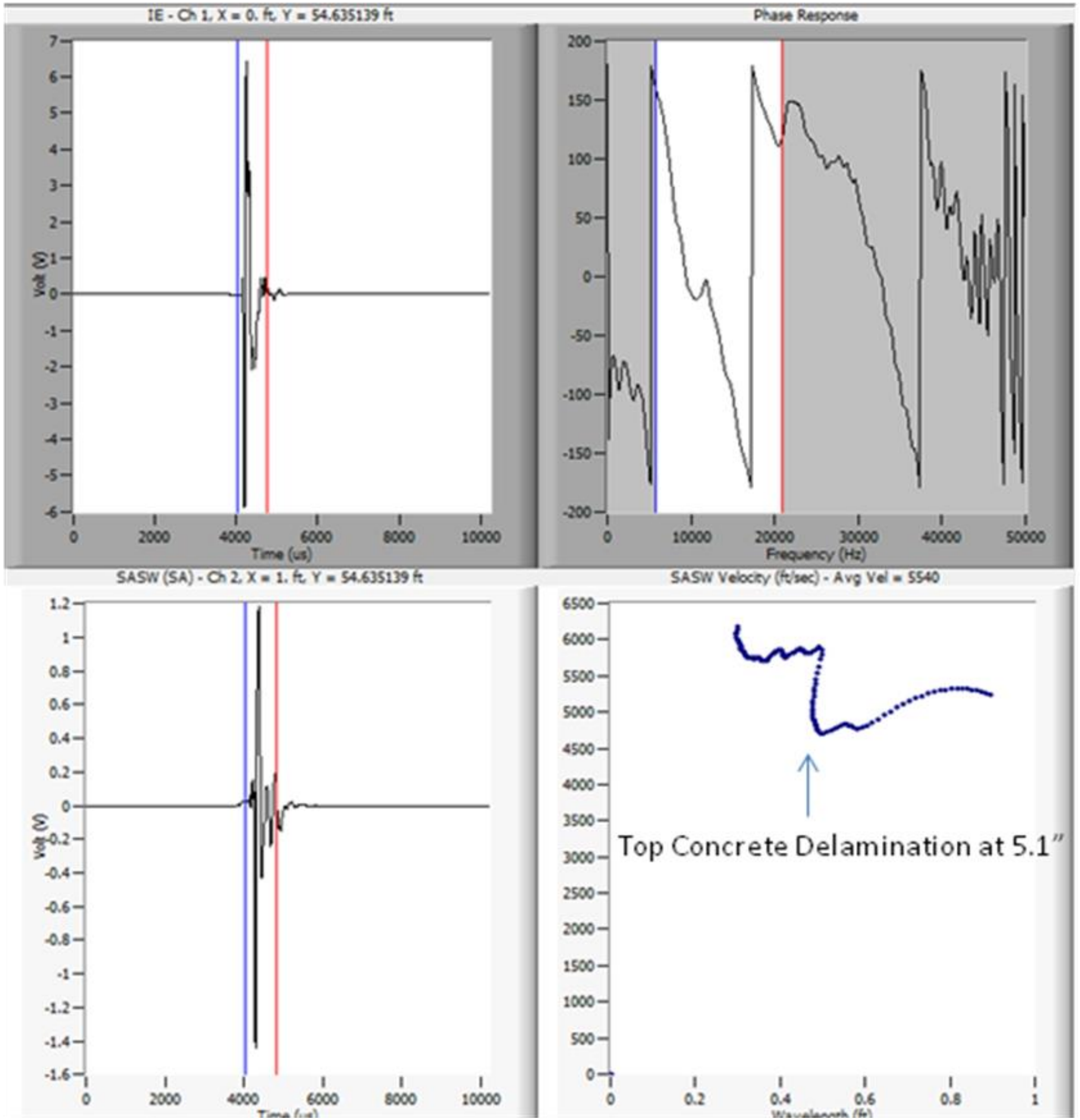
Findings – Bonded Asphalt on Sound Concrete



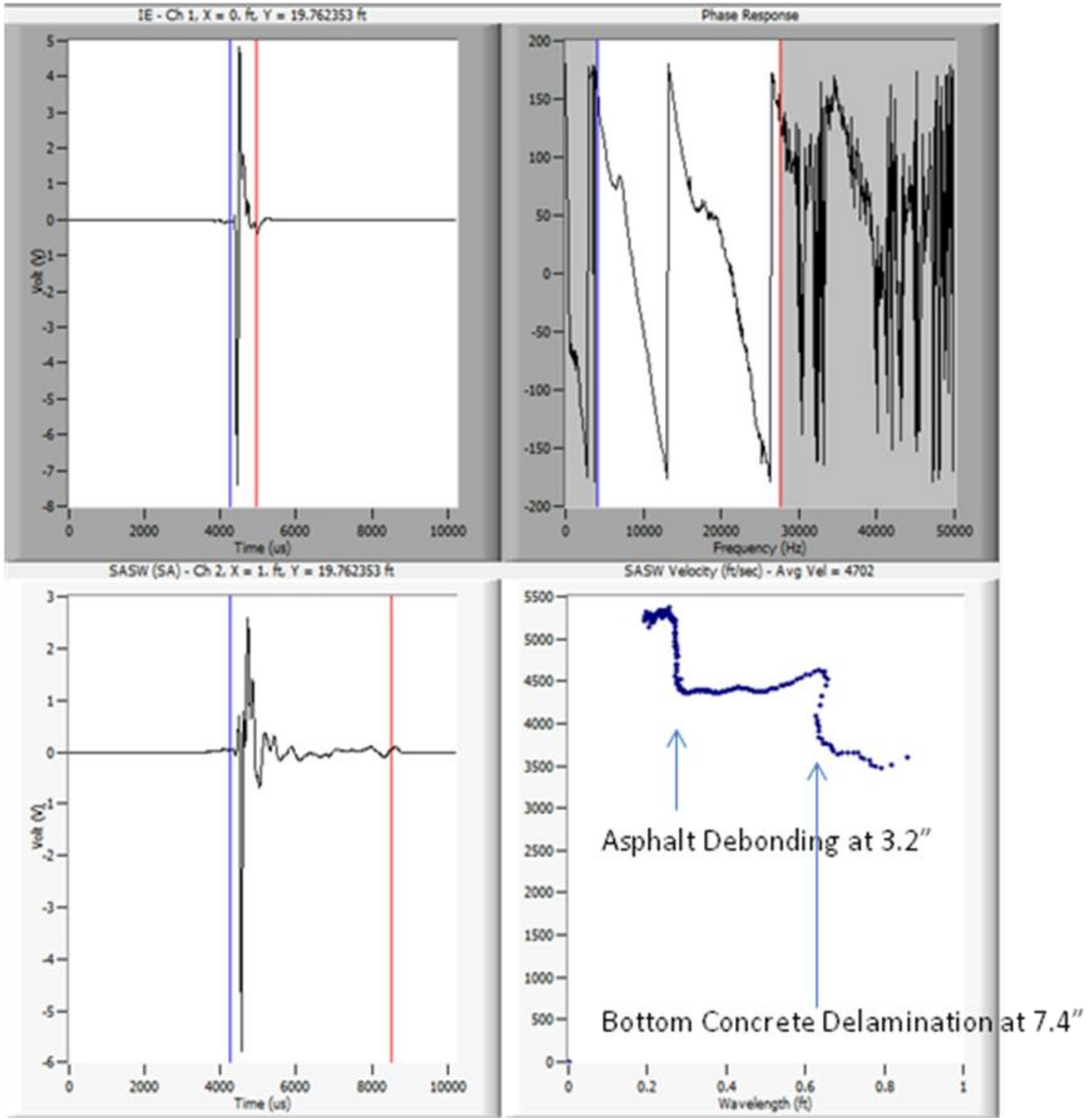
Sound Concrete with Asphalt Debonding



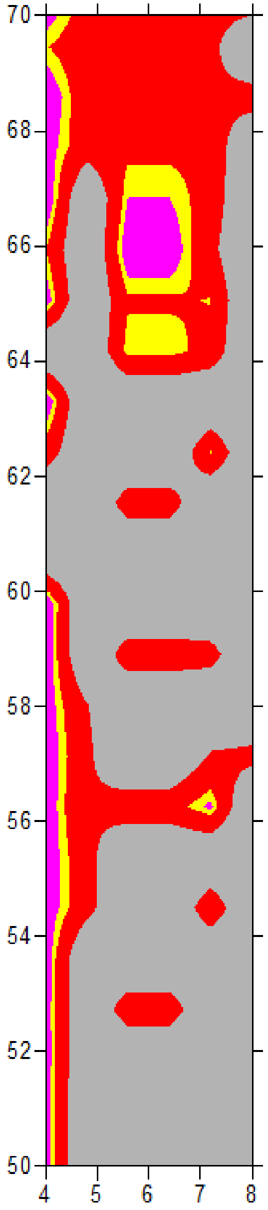
Bonded Asphalt on Concrete with Top Delamination

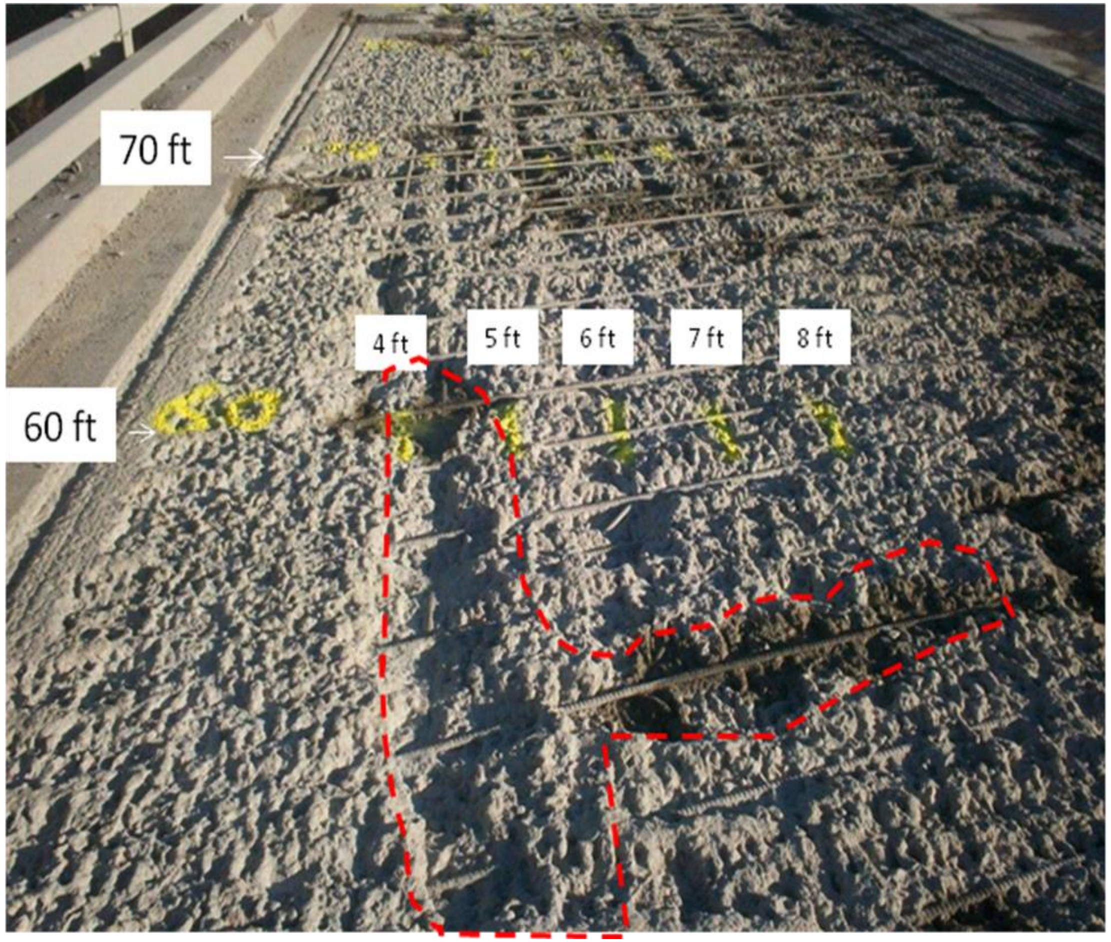


Debonded Asphalt / Concrete with Bottom Delamination



Ground Truthing - Hydrodemolition to reveal Delaminations





Bridge Deck Scanner with IE/SASW on Cart on Virginia Asphalt Overlaid Deck

BDS Conclusions

- A Bridge Deck Scanner (BDS) was achieved using ground contact rolling transducers wheels
- The system can be equipped with 2 – 6 wheels
- The BDS can performed
  - Impact Echo tests from all wheels for concrete deck applications
  - Impact Echo tests from the first wheel and the Spectral Analysis of Surface Waves from both wheels for asphalt overlay decks
- Although the speed is limited, each scan covers large areas in one run
- The top delamination tests results were correlated well with the delamination maps from chain drag and core results for concrete decks
- The top delamination tests results were correlated well with the results from hydro blasting for asphalt overlay decks

Bridge Deck Scanner (BDS) Summary

- Over 25 Bridge Decks tested to date for delamination and void/honeycomb concerns with Impact Echo Scanning (IES) and other nondestructive evaluation (NDE) methods

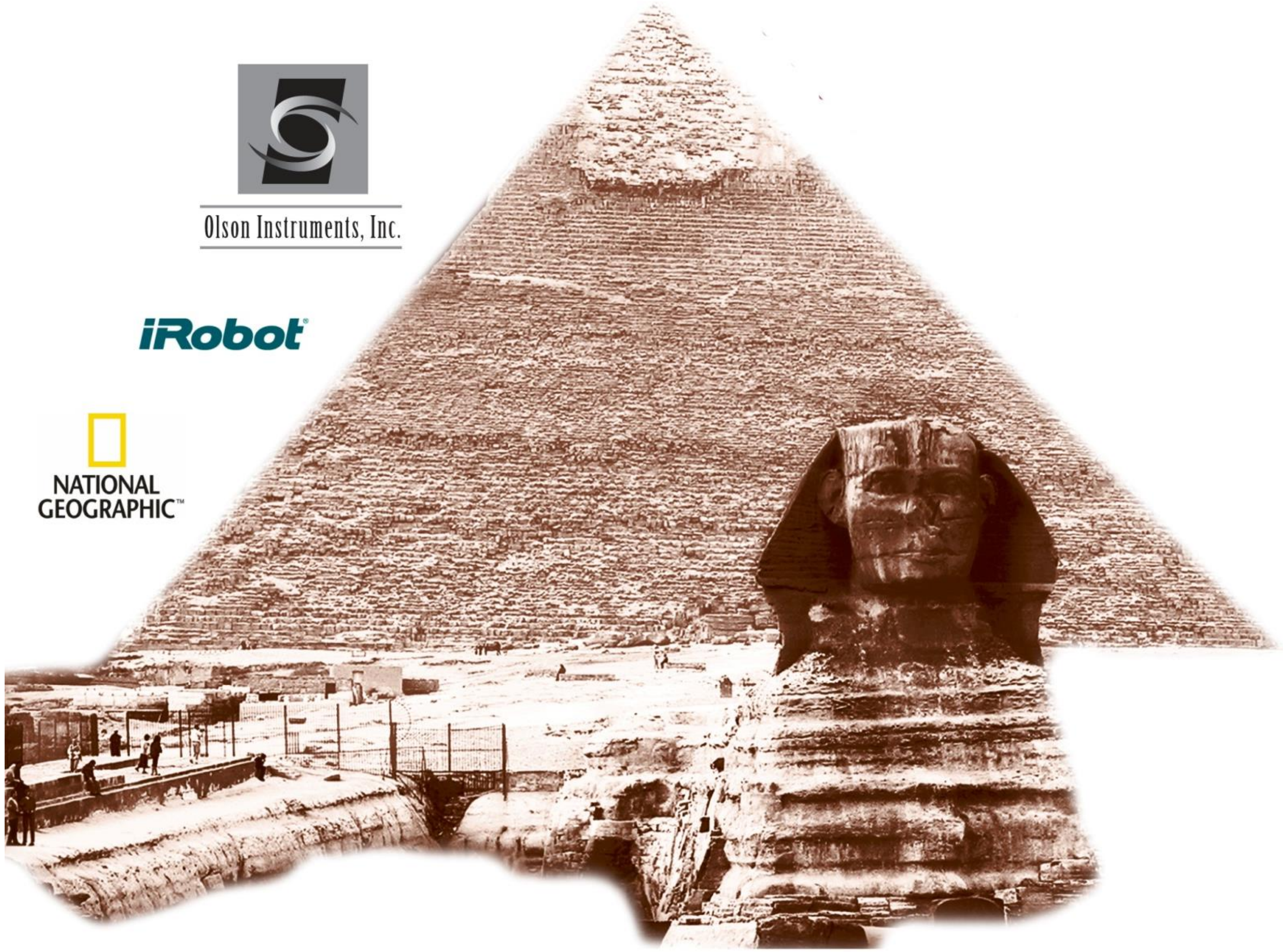
- BDS Impact Echo Scanning (IES) had the most resolution of Top Delaminations versus Infrared, Acoustic Sounding and Ground Penetrating Radar

- BDS IES results compared well with Chain Drag Acoustic Sounding (AS) and Ground Penetrating Radar (GPR) results with improved accuracy – Infrared Thermography (IRT) was not as accurate

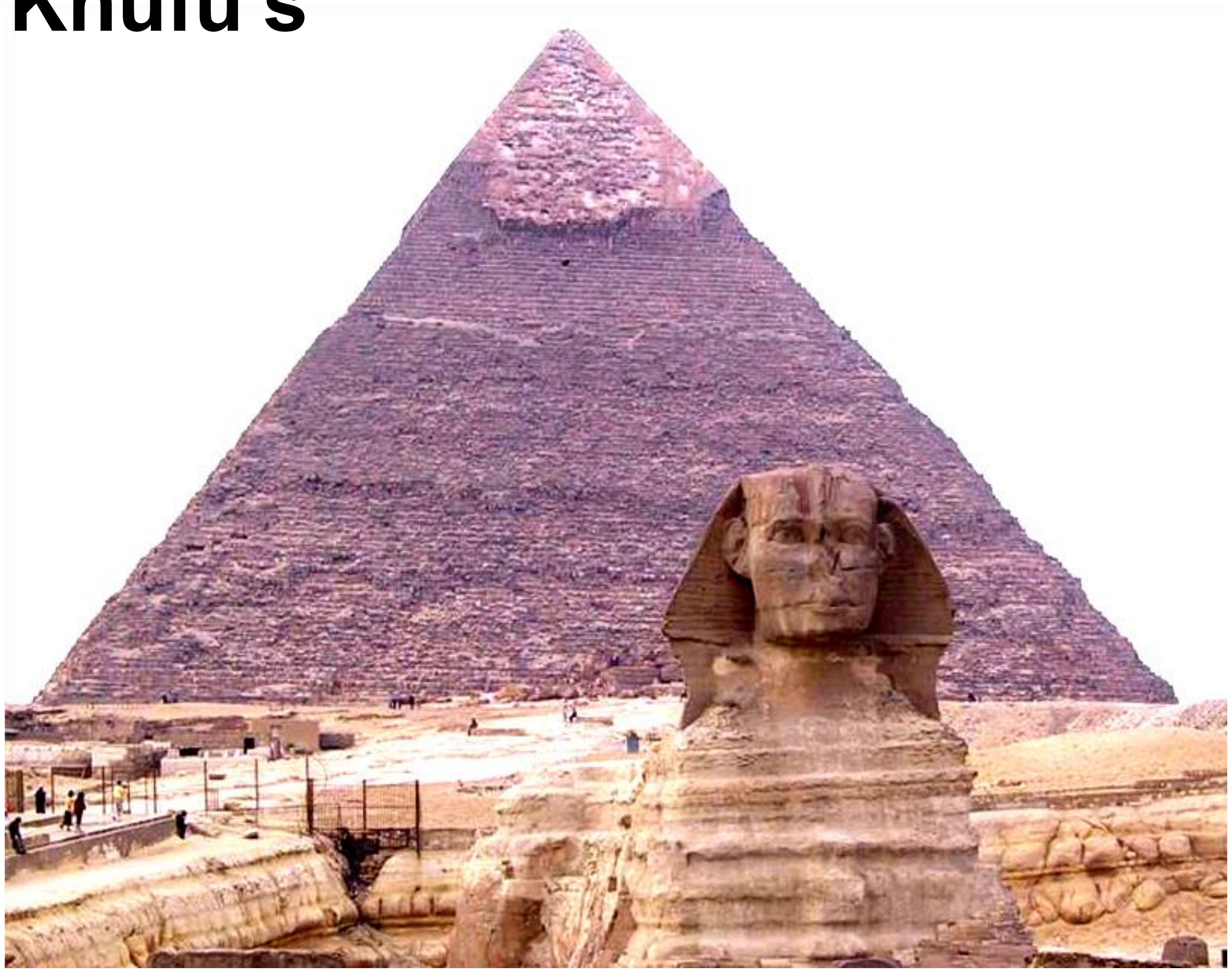
- BDS IES identified bottom delaminations as well. GPR, AS, and IRT methods are not sensitive to bottom delaminations when applied from the top of a deck

- BDS SASW tests found to be sensitive to deck delaminations below asphalt overalay as well as concrete cracking from freeze-thaw, alkali-silica reactions and general deck concrete quality

Olson Instruments Concrete Thickness Gauge used by iRobot for National Geographic/Fox Television Special *Beyond the Closed Door* in September, 2002



Khufu’s son Khafre’s Pyramid and Sphinx – built on a hill so it appears higher than Khufu’s



Case Study II: IE Test for Thickness Determination

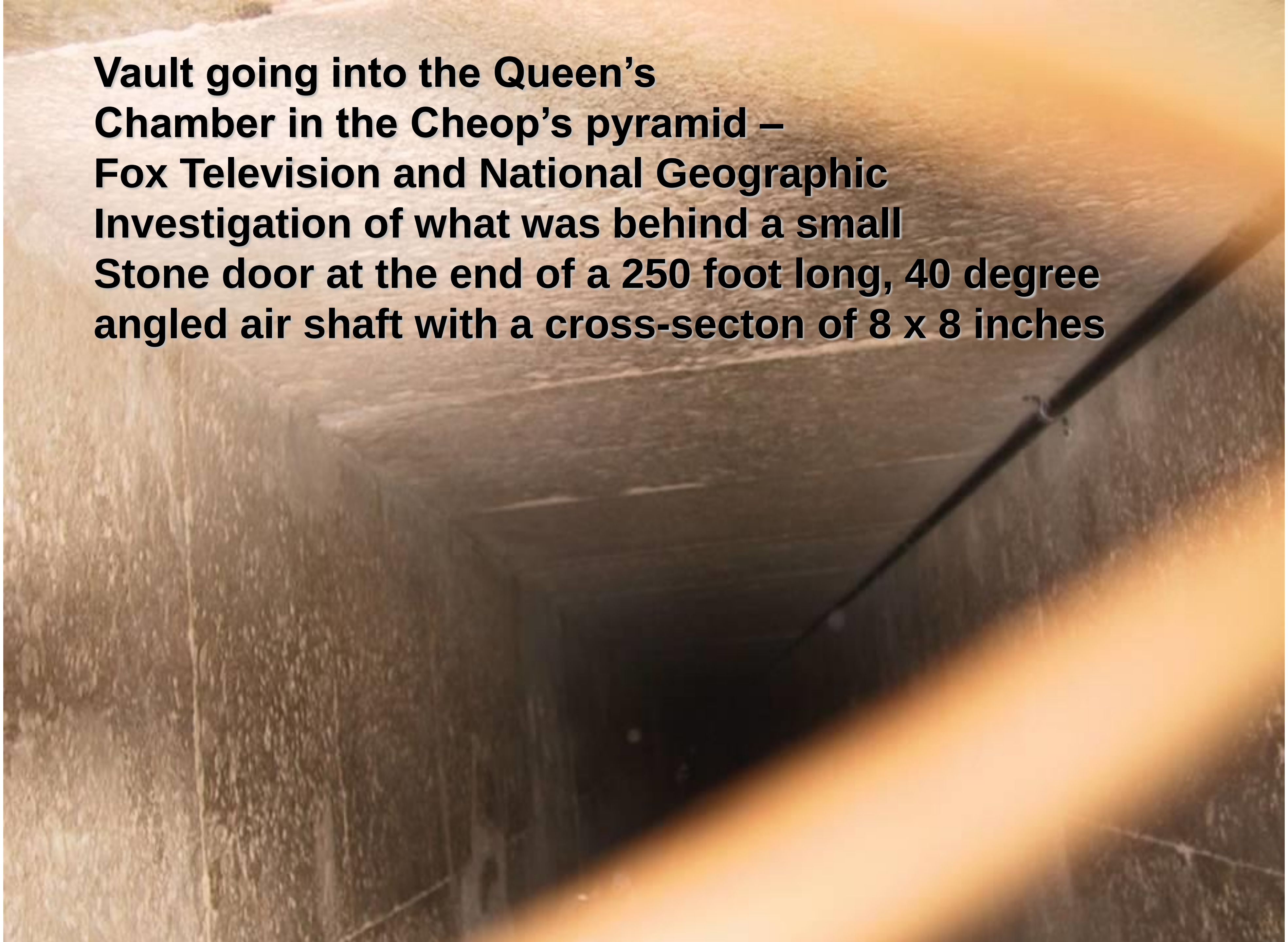
North Side Entrance to Khufu's (Cheop's) Pyramid – World's Tallest Building at 481 ft from 2650 BC until 1800's in Paris

Case Study II: IE Test for Thickness Determination

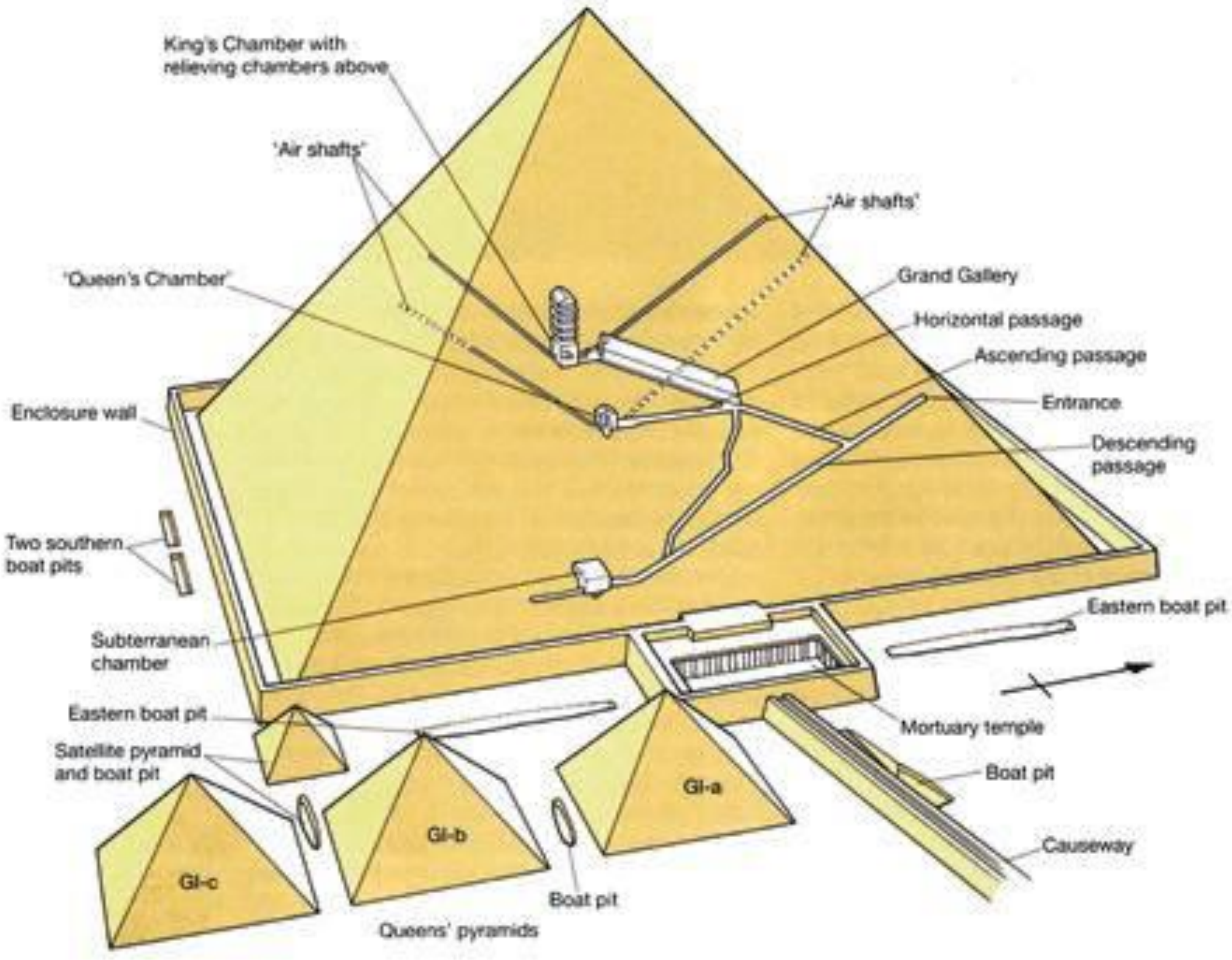
Stairs descending from the King’s tomb in the Cheops Pyramid

Case Study II: IE Test for Thickness Determination

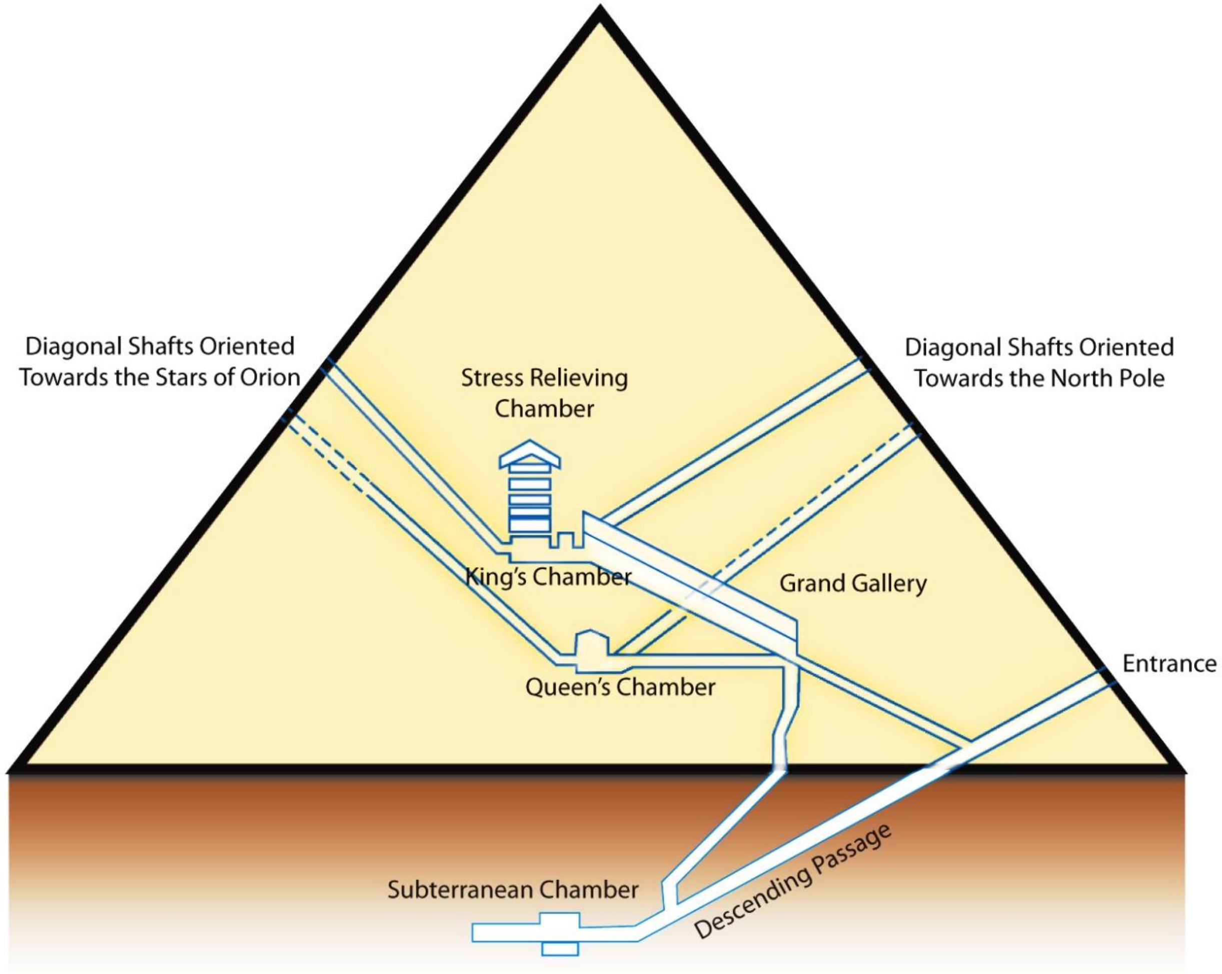
Corbeled Hallway going up into Pharaoh Khufu's Chambers of the Great Pyramid of Giza


Vault going into the Queen’s
Chamber in the Cheop’s pyramid –
Fox Television and National Geographic
Investigation of what was behind a small
Stone door at the end of a 250 foot long, 40 degree
angled air shaft with a cross-secton of 8 x 8 inches

Cheops or Khufu's Pyramid at Giza, Egypt

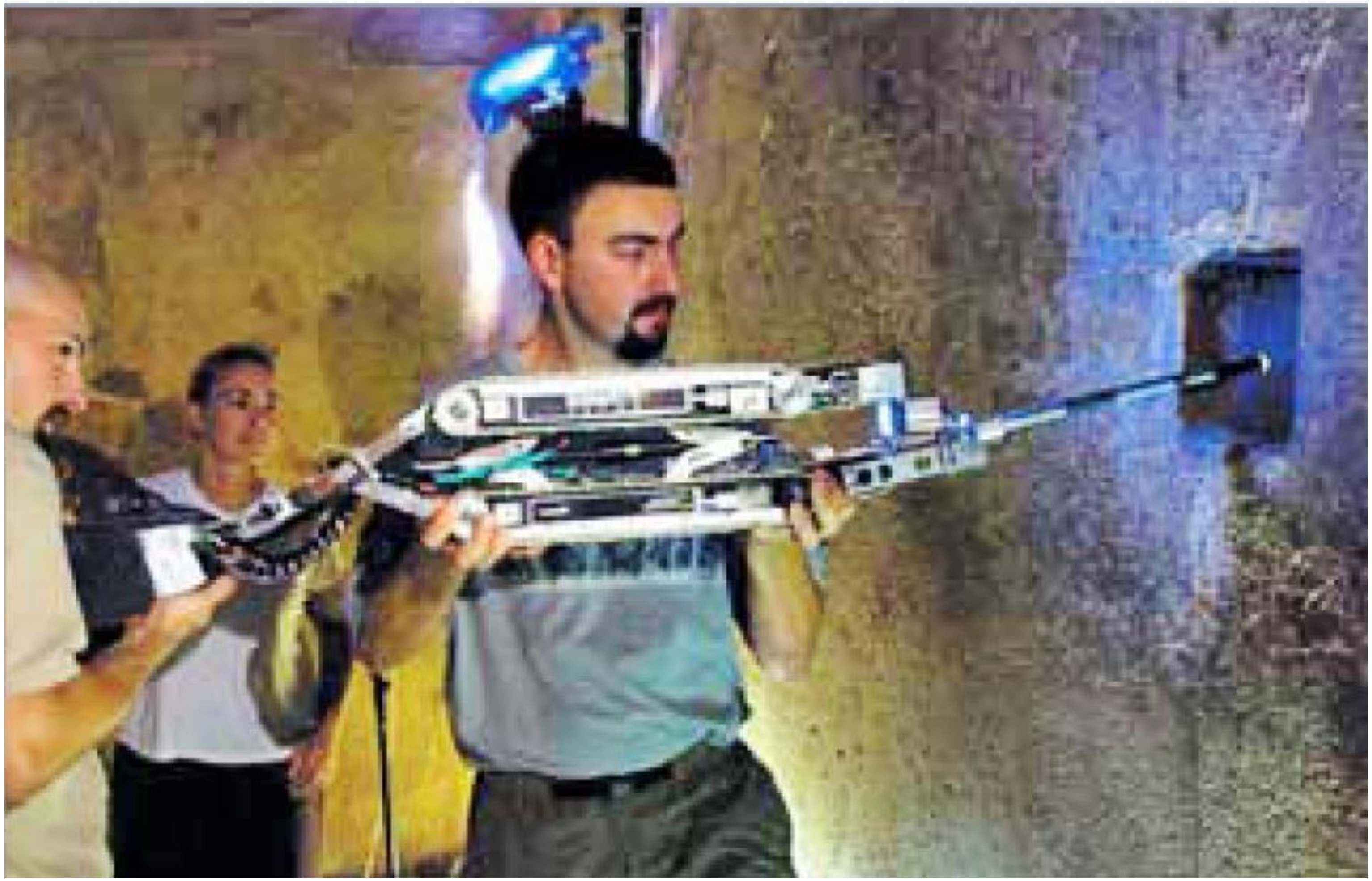


Khufu’s Great Pyramid Chambers

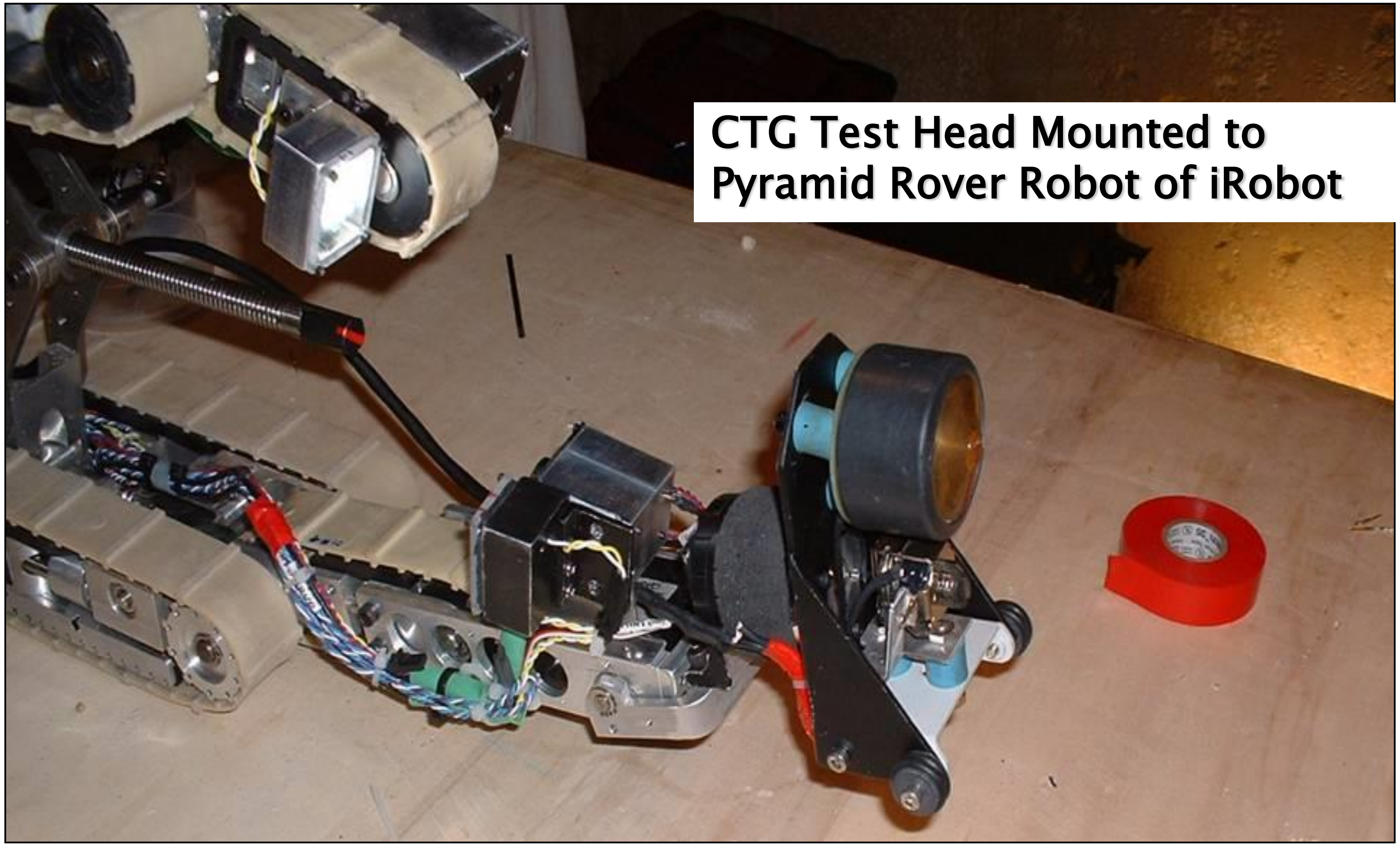


Queen’s Chamber & South Air Shaft that was investigated

iRobot Pyramid Rover Robot with video camera being inserted into South Airshaft



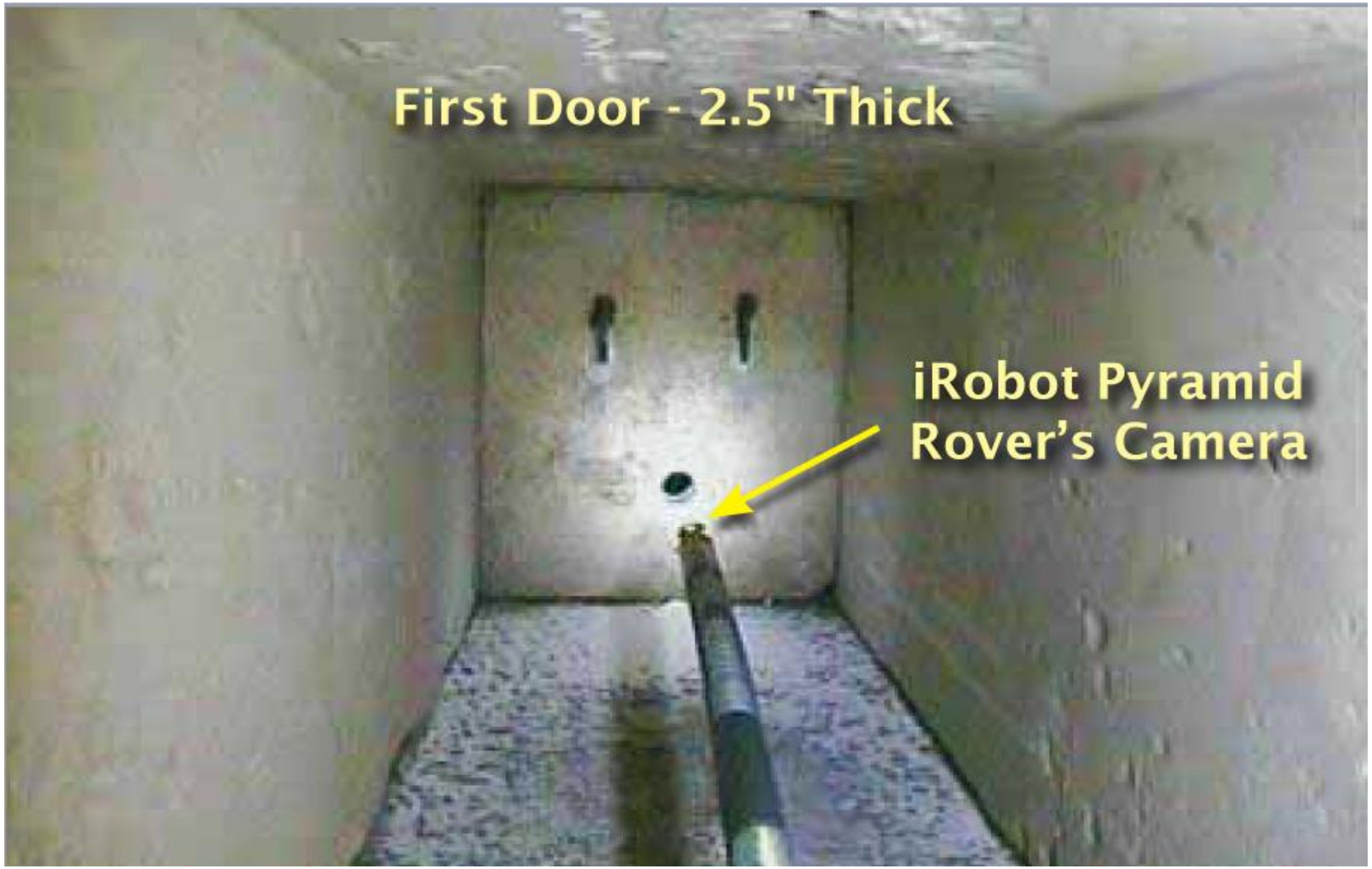
Case Study II: IE Test for Thickness Determination



Case Study II: IE Test for Thickness Determination

CTG Test Head on Gantenbrink's Door – Impact Echo predicted to be 2 to 2.5 inches thick and drilling found door was 2.4 inches thick. Note 2 copper pins at top of 8 x 8 inch (200 x 200 mm) stone door

Gantenbrink's Door with 2 copper pins and borescope camera to be inserted in 31 mm diameter hole



What was found? Another door 16 inches away with cracks in it! The mystery continues.

Slab Impulse Response Combined with Ground Penetrating Radar for Void Detection below Slabs

Used to Locate and Define Voids Under Spillways, Roadways, Building Slabs, Tunnel Liners, Pipe Walls, and other Rigid Pavements

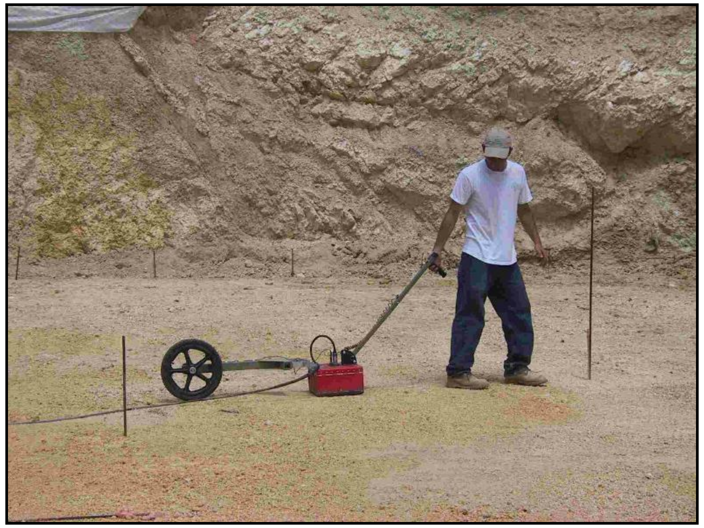
Outline

- **NDT&E methods of Slab Impulse Response, Ground Penetrating Radar and Video Borescope**
- **Field Project background**
- **Survey design and data collection procedures**
- **Example results**
- **Combined NDE results - data presentation and interpretation for subgrade void evaluation**
- **Corehole Ground-truthing**

  and conclusion

NDT&E Methods

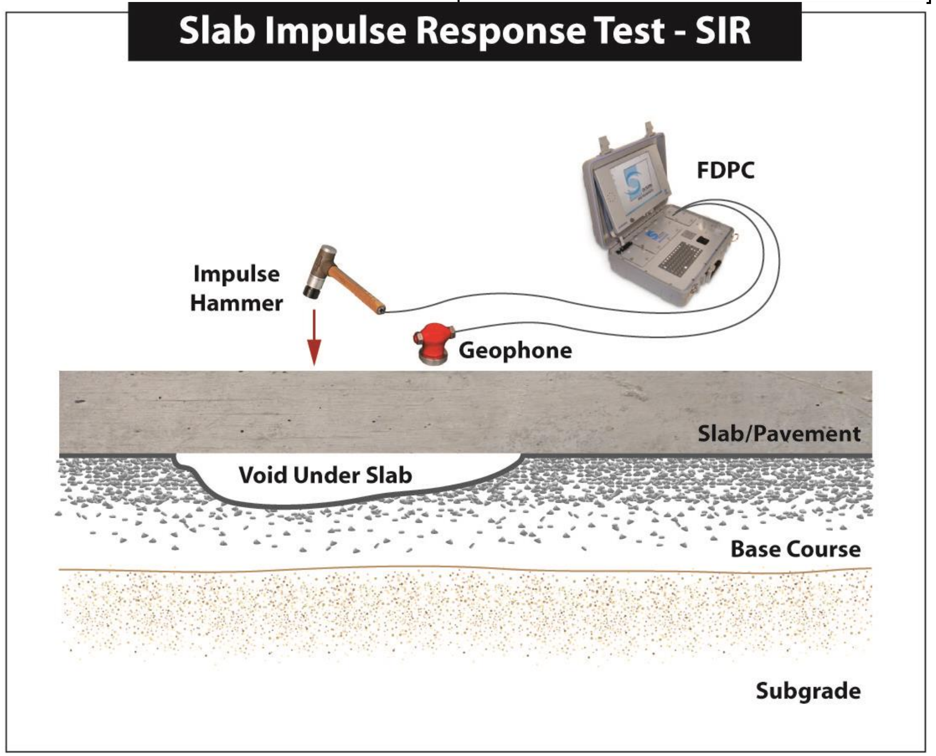
- **Ground Penetrating Radar (GPR)**
  - **Electromagnetic wave reflection – 400 MHz Antenna on wheel**
- **Slab Impulse Response (Slab IR)**
  - **Acoustic modal vibration method – 3 lb impulse hammer and geophone (velocity transducer)**
- **Complementary tools for determining areas of poor subgrade support or voids**



Slab Impulse Response Method

- Olson Instruments Freedom NDT PC with Slab IR system (SIR-1)
- 3-lb instrumented hammer impacts and geophone records time domain data
    - Wilcoxson velocity transducer because of slope – Also used for tunnel liners
- Data converted to frequency domain via FFT
- Indicators
    - Amplitude of resonance
    - Frequency of resonance

Freedom Data PC – Slab IR Module



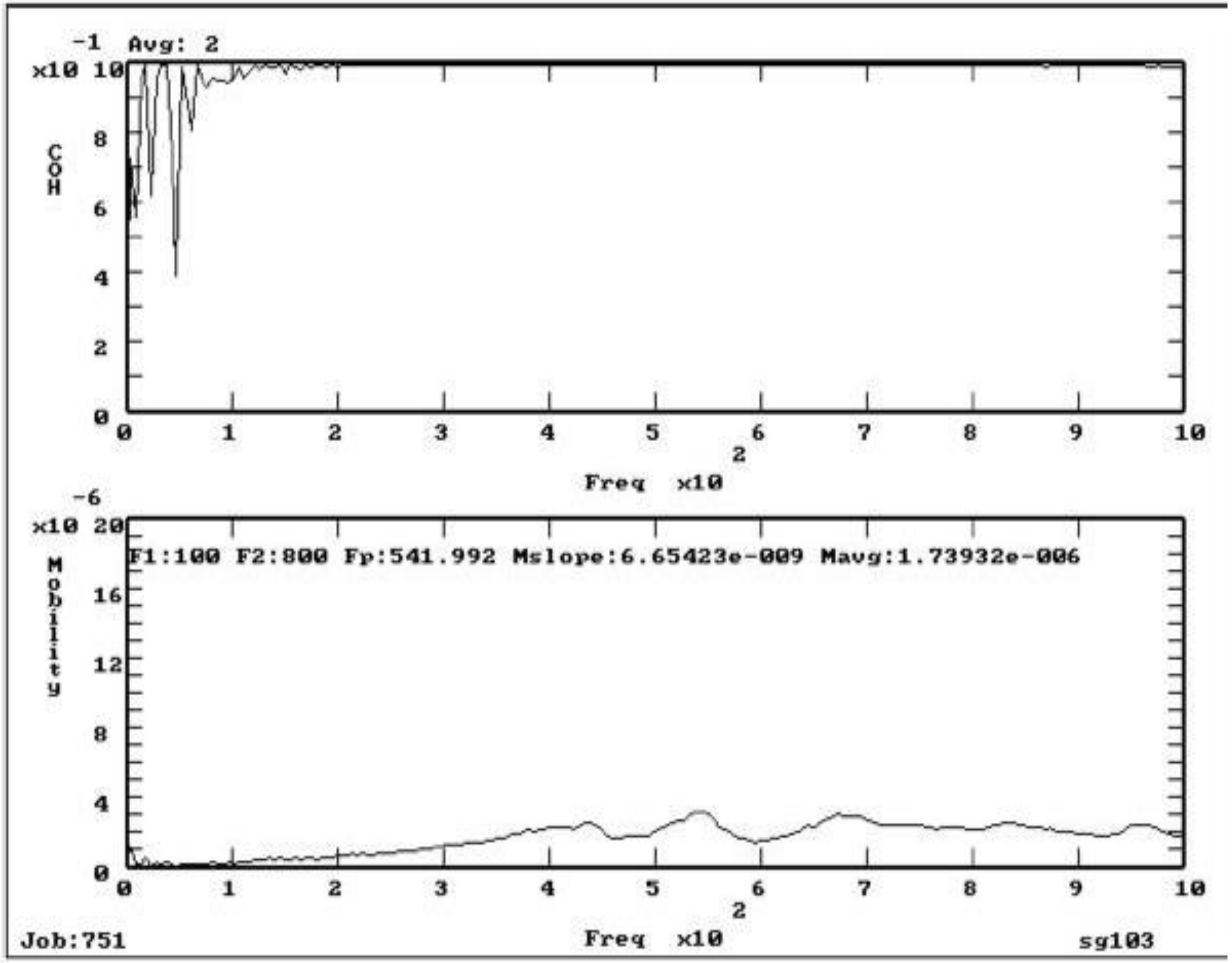
Freedom Data PC – Slab IR System

- Model available
  - SIR-1: includes a 3 lb (1.4 kg) hammer, 4.5 Hz vertical geophone and any direction velocity transducer

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

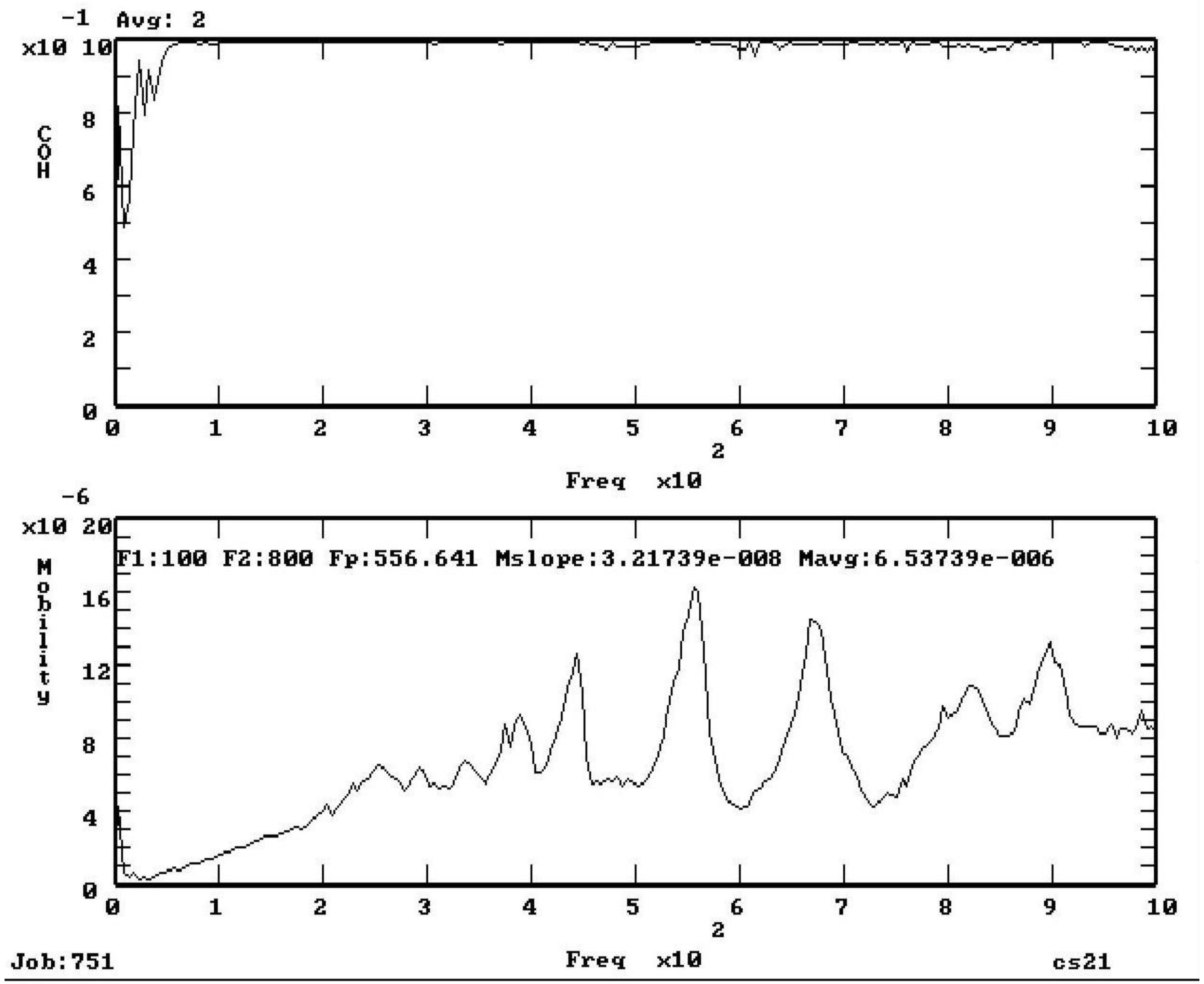
Example Slab Impulse Response record showing normal thickness (6.7 inches) concrete on a freight rail bridge

- Note the low mobility and flat slope indicative of the 6.7 inch thick slab of a box girder



Example Slab Impulse Response record showing thin concrete (2.6 inches) on a light rail bridge

- Note irregular and higher mobility and steeper slope indicative of the much greater flexibility of the 2.6 inch thick (from IE tests) bottom slab of the box girder

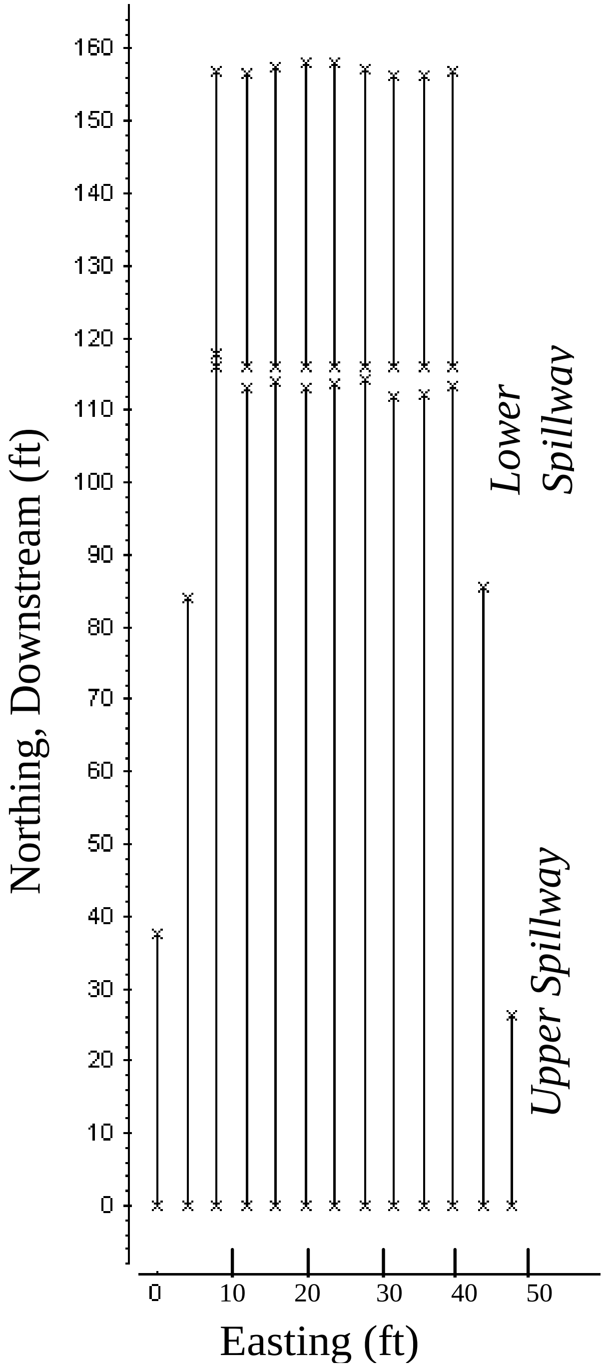


Spillway Project Background

- **Spillway Characteristics**
  - **Alpine reservoir dam concrete spillway in Colorado at nearly 10,000 ft above sea level**
  - **Reservoir capacity ~ 800 acre-ft serves as water source for nearby town**
  - **Dimensions are 156 ft long x 52 ft wide at top, tapering to 32 ft wide at bottom**
  - **6-14 inch thick concrete, reinforced with one mat at nominally 12 inches**
- **Reasons for NDT&E**
  - **Observed water seepage at joints and concrete spalling**
  - **Prior hammer sounding investigation by 2 consultants**
  - **Drilling investigation performed by local municipality**

GPR Field Survey

- **400 MHz antenna, 48 pulses per foot**
- **Survey wheel records distance**
- **Data collected in 3-D fashion with unidirectional parallel lines at 4 ft intervals**
- **Spillway split into upper and lower portions**
- **Scanning from spillway crest to bottom for each portion**
- **Treacherous footing because of moss. Felt-bottom shoes worn**



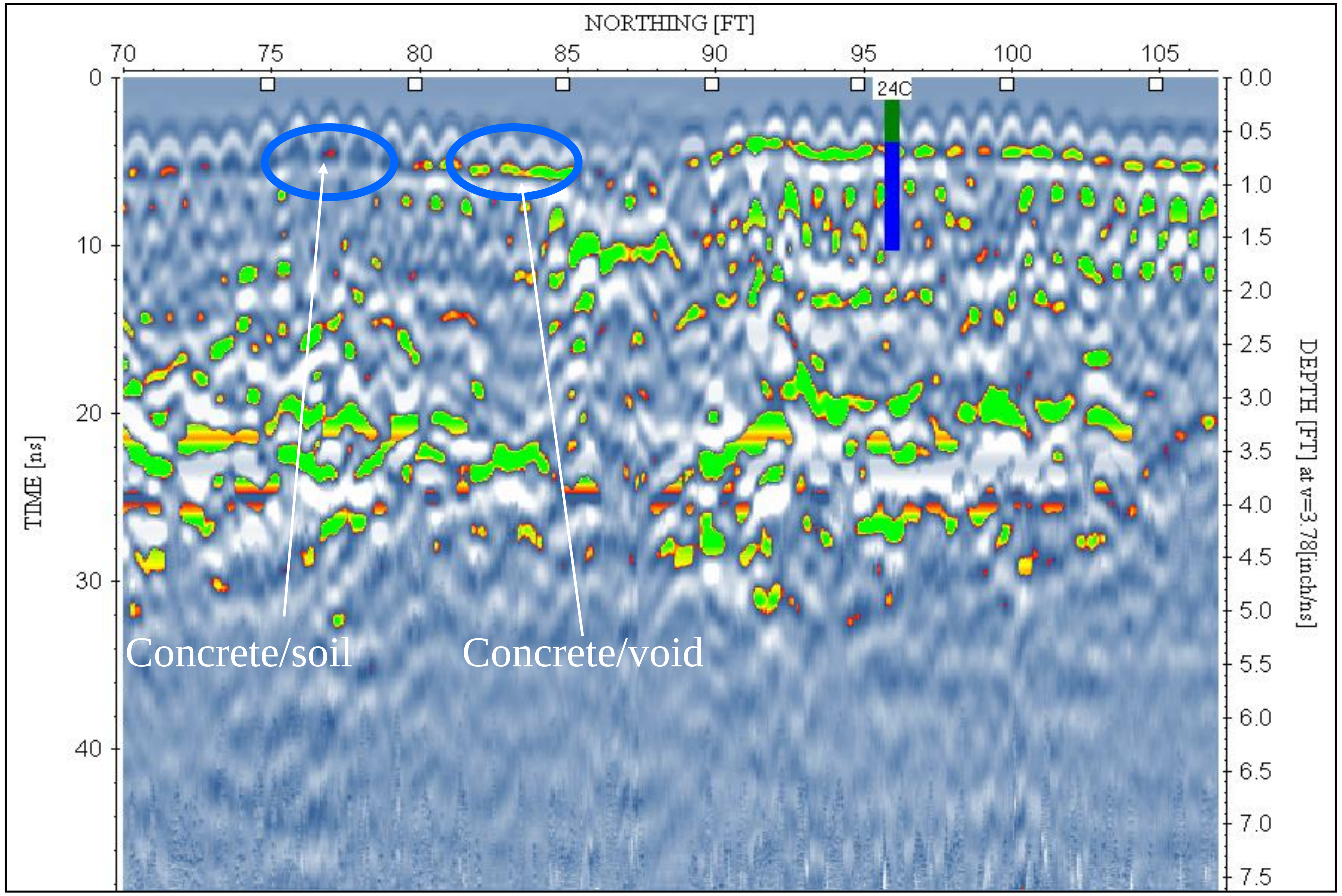
Slab IR Field Survey

- **Data collected at a 4 x 4 ft grid**
- **3 hammer impact (records) collected at each point and averaged**
- **428 data points total**
- **Centerline of the spillway, running longitudinally for more than 156 ft downstream named ‘C’**
- **Longitudinal lines designated at 4 ft intervals from right of center eastward as R1 through R6 and at 4 ft intervals from left of center westward as L1 through L6 looking downstream from the spillway crest**
- **Survey began 2 ft downstream of the reservoir shore edge through line 40 at 4 ft intervals**

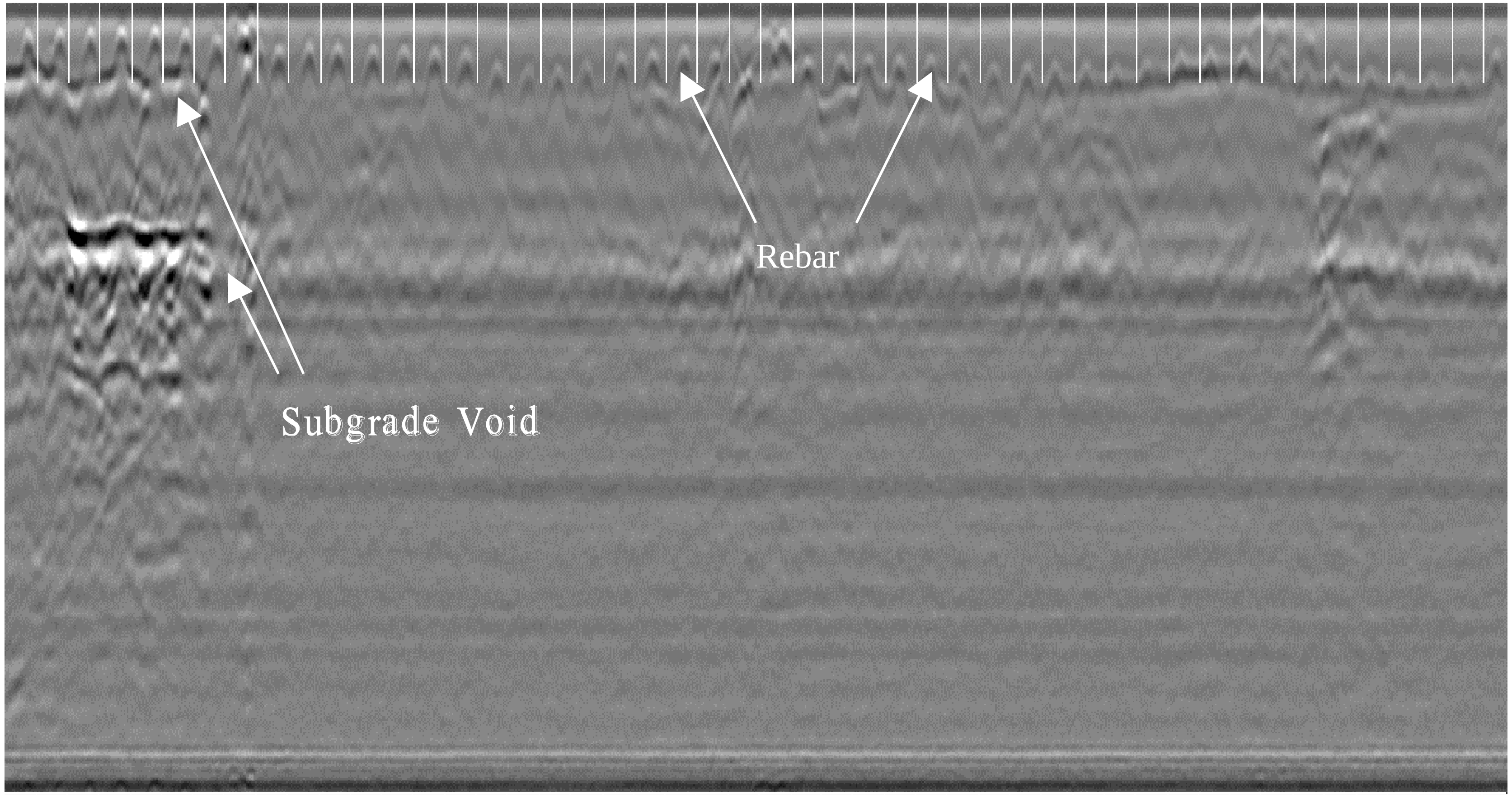
GPR Example Results

- **Slab bottom/subsurface amplitude reflection = bright spot analysis**
- **$R = (e_{rU}^{0.5} - e_{rL}^{0.5}) / (e_{rU}^{0.5} + e_{rL}^{0.5})$**

Material	e_r	R
Concrete	9.8	---
Void (air)	1.0	0.52
Soil	4.0	0.22



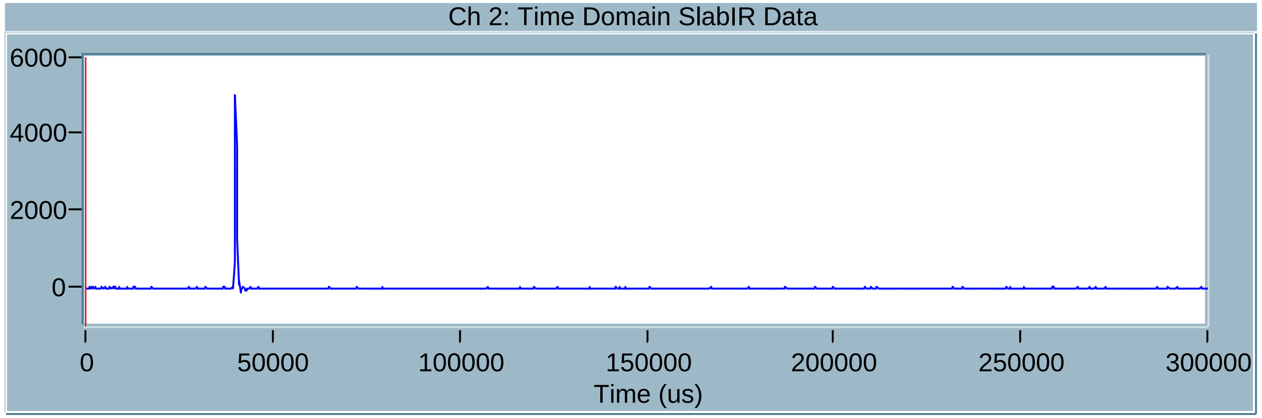
GPR Example Results – Spillway with Water Flow Underneath



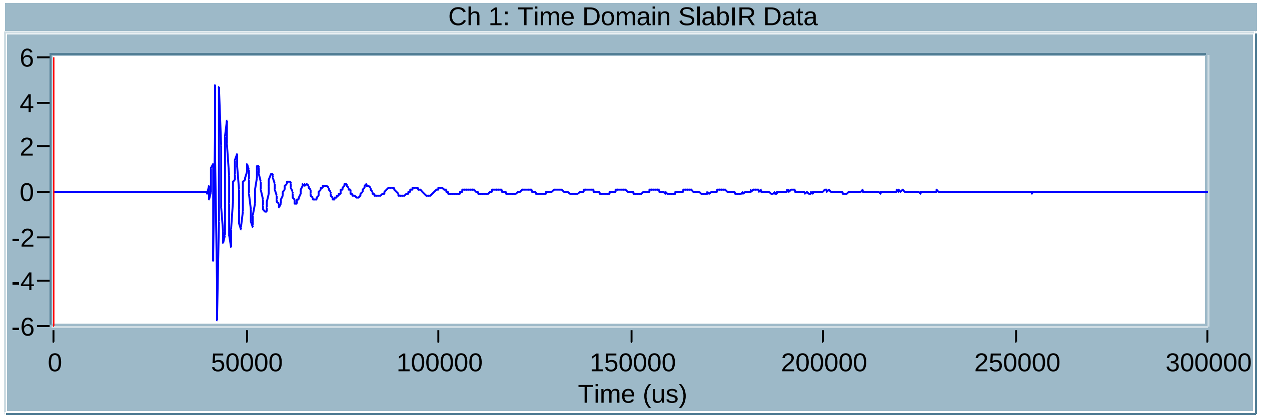
Slab IR Data Processing

- Time domain data of hammer input and receiver output converted to frequency domain by FFT
- Transfer function normalizes receiver spectrum by hammer spectrum

Hammer Signal

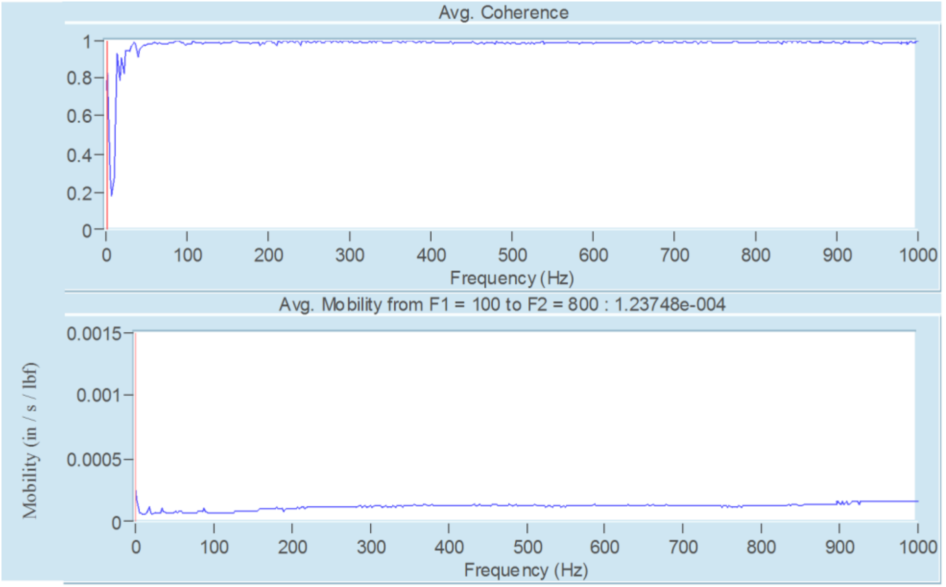


Receiver Signal

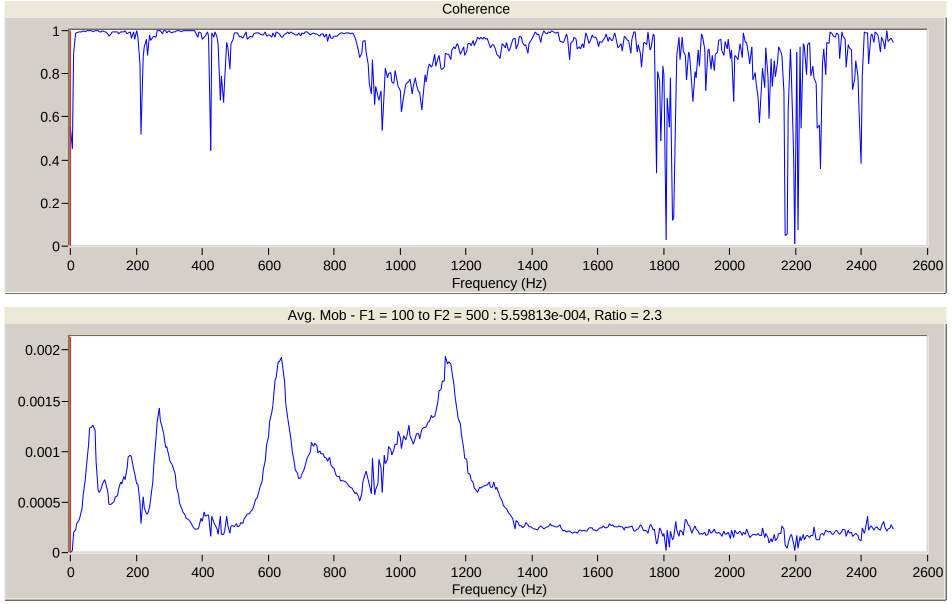


Slab IR Example Results

- Subgrade support condition evaluation parameters
  - mean mobility (in/sec/lbf)
  - shape of the mobility plot at frequencies above the initial straight-line portion of the curve (between 100 to 800 Hz in this investigation)
  - initial slope of the mobility plot gives the low-strain flexibility (in/lbf) of the spillway-subgrade system
- Interpretation Pitfalls
  - Slab thickness
  - Local reinforcement
  - Local joints/seams

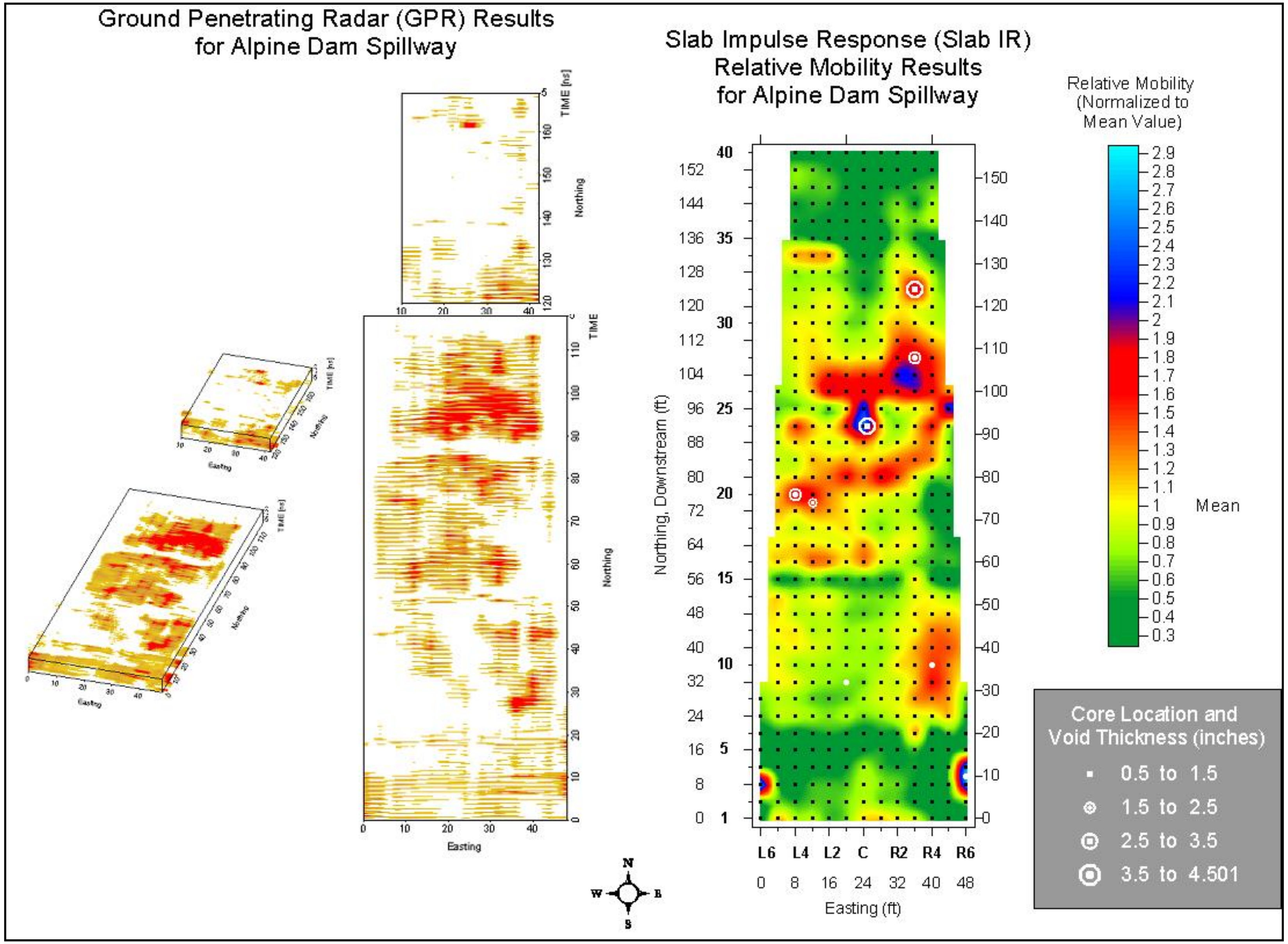


Good subgrade support – low, smooth mobility



Poor subgrade support – high, irregular mobility

Combined NDE Results



Ground-truthing

- Coring locations recommendations based on NDE results
- Video borescope probe for motion and still pictures
- Excellent correlation – extensive subgrade voids found in all coreholes

Thank You

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Questions?

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