Virginia Center *for* Transportation
INNOVATION
& RESEARCH

Nondestructive Measurements Using Mechanical Waves in Reinforced Concrete Structures

http://www.virginiadot.org/vtrc/main/online_reports/pdf/14-r8.pdf

STEPHEN R. SHARP, Ph.D., P.E.
Senior Research Scientist

CELIK OZYILDIRIM, Ph.D., P.E.
Principal Research Scientist

Final Report VCTIR 14-R8

VIRGINIA CENTER FOR TRANSPORTATION INNOVATION AND RESEARCH
530 Edgemont Road, Charlottesville, VA 22903-2454

www.VTRC.net

Standard Title Page - Report on Federally Funded Project

1. Report No.:
FHWA/VCTIR 14-R8

2. Government Accession No.:

3. Recipient's Catalog No.:

4. Title and Subtitle:
Nondestructive Measurements Using Mechanical Waves in Reinforced Concrete Structures

5. Report Date:
February 2014

6. Performing Organization Code:

7. Author(s):
Stephen R. Sharp, Ph.D., P.E., and Celik Ozyildirim, Ph.D., P.E.

8. Performing Organization Report No.:
VCTIR 14-R8

9. Performing Organization and Address:
Virginia Center for Transportation Innovation and Research
530 Edgemont Road
Charlottesville, VA 22903

10. Work Unit No. (TRAIS):

11. Contract or Grant No.:
99207

12. Sponsoring Agencies' Name and Address:

Virginia Department of Transportation
1401 E. Broad Street
Richmond, VA 23219

Federal Highway Administration
400 North 8th Street, Room 750
Richmond, VA 23219-4825

13. Type of Report and Period Covered:
Final

14. Sponsoring Agency Code:

15. Supplementary Notes:

16. Abstract:

This study evaluated various techniques that use mechanical waves for the evaluation of critical concrete properties, such as proper consolidation of the concrete during placement and strength development; changes in modulus; and the detection of cracks, voids, and delaminated regions. The methods evaluated were ultrasonic shear-wave tomography, ultrasonic pulse velocity, crosshole sonic logging, sonic echo-impulse response, spectral analysis of surface waves, and the use of an impact echo scanner on pavements and bridge structures.

Ultrasonic shear-wave tomography can be successfully used to determine the major distressed areas in pavements. Crosshole sonic logging can detect voids in drilled shafts and can indicate concrete performance and quality. Sonic echo-impulse response can reliably detect voids but is not always able to establish a precise location because of the potential variability in wave velocity. However, it can still provide useful thickness or depth information. In addition, detection of distress is limited by the embedded length-to-diameter ratios of the foundation element being examined. The use of ultrasonic pulse velocity can improve the accuracy of sonic echo–impulse response measurements by providing the actual velocity of the concrete being evaluated. Use of the impact echo scanner can provide delamination data for structures with smooth surfaces.

In addition to detecting the condition of the concrete elements, these methods can be used to help determine compliance with end-result specifications. Quality control and acceptance using end-result specifications requires at least three test results to determine variability, which can be easily obtained using nondestructive test methods.

The results regarding spectral analysis of surface waves were promising, but additional validation work is required to determine the abilities of this technique to assess asphalt-overlaid concrete decks.

This study showed that nondestructive mechanical wave methods can be successfully used in determining concrete quality and the extent of distress in concrete structures. The study recommended that these methods be used by the Virginia Department of Transportation for condition assessment. The next step is to continue collecting data on pavements and bridge structures using these techniques.

17 Key Words:
Concrete, impact echo, mechanical wave, NDE, spectral analysis of surface waves, sonic echo, impulse response, ultrasonic

18. Distribution Statement:
No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.

19. Security Classif. (of this report): Unclassified	20. Security Classif. (of this page): Unclassified	21. No. of Pages: 32	22. Price:

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

FINAL REPORT

NONDESTRUCTIVE MEASUREMENTS USING MECHANICAL WAVES IN REINFORCED CONCRETE STRUCTURES

Stephen R. Sharp, Ph.D., P.E.
Senior Research Scientist

Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Center for Transportation Innovation and Research
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

February 2014
VCTIR 14-R8

DISCLAIMER

ABSTRACT

This study evaluated various techniques that use mechanical waves for the evaluation of critical concrete properties, such as proper consolidation of the concrete during placement and strength development; changes in modulus; and the detection of cracks, voids, and delaminated regions. The methods evaluated were ultrasonic shear-wave tomography, ultrasonic pulse velocity, crosshole sonic logging, sonic echo-impulse response, spectral analysis of surface waves, and the use of an impact echo scanner on pavements and bridge structures.

Ultrasonic shear-wave tomography can be successfully used to determine the major distressed areas in pavements. Crosshole sonic logging can detect voids in drilled shafts and can indicate concrete performance and quality. Sonic echo-impulse response can reliably detect voids but is not always able to establish a precise location because of the potential variability in wave velocity. However, it can still provide useful thickness or depth information. In addition, detection of distress is limited by the embedded length-to-diameter ratios of the foundation element being examined. The use of ultrasonic pulse velocity can improve the accuracy of sonic echo–impulse response measurements by providing the actual velocity of the concrete being evaluated. Use of the impact echo scanner can provide delamination data for structures with smooth surfaces.

In addition to detecting the condition of the concrete elements, these methods can be used to help determine compliance with end-result specifications. Quality control and acceptance using end-result specifications requires at least three test results to determine variability, which can be easily obtained using nondestructive test methods.

The results regarding spectral analysis of surface waves were promising, but additional validation work is required to determine the abilities of this technique to assess asphalt-overlaid concrete decks.

This study showed that nondestructive mechanical wave methods can be successfully used in determining concrete quality and the extent of distress in concrete structures. The study recommended that these methods be used by the Virginia Department of Transportation for condition assessment. The next step is to continue collecting data on pavements and bridge structures using these techniques.

FINAL REPORT

NONDESTRUCTIVE MEASUREMENTS USING MECHANICAL WAVES IN REINFORCED CONCRETE STRUCTURES

Stephen R. Sharp, Ph.D., P.E.
Senior Research Scientist

Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist

INTRODUCTION

Techniques that use mechanical (stress) waves have proven to be reliable tools for nondestructively evaluating components in the field, including assessing the condition of concrete. For example, the consolidation of the concrete shortly after placement and strength development, as well as the detection of cracks, voids, and delaminated regions, can be accomplished through various mechanical wave methods.

The extraction of cores for the inspection of pavements and bridge decks both damages the structure and impedes traffic; therefore, nondestructive evaluation (NDE) of these structures is highly preferable. Ultrasonic shear-wave tomography (UST) is a promising technology for this application. Investigations of a UST device (Hoegh et al., 2011), commonly called MIRA, have shown its capacity for the detection of reinforcement, voids, cracking, delaminations, overlay debonding, and other anomalies in general. It is also capable of producing 3D models of the pavement's internal structure for a better evaluation of the condition of the pavement.

In drilled shaft construction, integrity testing has always been problematic because of underground placement, allowing for limited observation, and the size of the element. Crosshole sonic logging (CSL), which is a modification of the ultrasonic pulse velocity (UPV) technique, has been identified as an evaluation method capable of overcoming these difficulties. The technology can be adapted to allow for the detection of voids and improper consolidation in larger elements while also defining areas of stronger and weaker concrete within the shaft. However, it will not provide information on the soundness of the concrete in the cover depth region, since this region is outside the area interrogated by the CSL transducers.

Sonic echo–impulse response (SE/IR) testing is a more versatile technology because it can be used in multiple applications, including the evaluation of deep foundations, such as drilled shafts, driven concrete, and timber piles, as well as thicker and deeper structural elements (more than 6 ft where impact echo [IE] is limited), such as piers, abutments, and thick tunnel walls. The technology is one of the more widely used mechanical wave methods today, as it has been used successfully to detect voids, breaks, cracks, and even debonding and delaminations with similar slab impulse response testing in accordance with ASTM C1740 (Standard Practice for Evaluating the Condition of Concrete Plates Using the Impulse-Response Method) (ASTM

International [ASTM], 2010a) within concrete structures. However, there is a depth limitation mainly in drilled shafts and driven piles that is a function of the surrounding soil and the length-to-diameter ratios exceeding 20:1 to 30:1 for deep foundation elements in stiffer soils and bedrock, as foundation bottom echoes may not be measurable because of attenuation of the wave energy.

IE testing using an IE scanner (IES) is a single point measurement technique that has been used to determine thickness or delamination in reinforced concrete. This device has been used in many applications where it is important to understand the size of a delaminated region so that additional structural analysis can be performed. For example, in Louisa County, Virginia, an IES was used to determine the size of a delaminated region, which was then used in conjunction with structural load testing and flexure analysis to assess the condition of the bridge (Lucas et al., 2004). In the current study, a more automated IES that is able to make a series of measurements along a linear path on a slow-rolling basis was tested.

Finally, spectral analysis of surface waves (SASW) with a bridge deck scanner (BDS), which can also conduct IE tests, was evaluated to determine if it could be used as a method of NDE to provide information on the condition of reinforced concrete. Although this technique has several applications that might be of value to the Virginia Department of Transportation (VDOT) (Tinkey et al., 2011), the focus of this study was the evaluation of the quality of concrete that has been overlaid with asphalt, as IE testing and chain dragging are typically ineffective at detecting delaminations attributable to corrosion when asphalt is on top of a concrete deck. Evaluation of an asphalt-overlaid concrete bridge deck in Colorado was successful, although stronger confirmation of damage detection was needed (Tinkey et al., 2013).

PURPOSE AND SCOPE

The purpose of this study was (1) to evaluate the ability of currently available NDE techniques that use mechanical waves for examining reinforced concrete (e.g., ultrasonic or IE techniques) to characterize physical properties and imperfections in various VDOT concrete pavements and structures; and (2) to determine if any of these nondestructive techniques could provide VDOT with a cost-effective method of gathering valuable information about concrete materials and in-place condition to verify compliance with end-result specifications (ERS).

To ensure the evaluation was thorough, a wide scope was used to determine which techniques should be evaluated. The only requirement was that the technique be nondestructive and use mechanical waves to assess the condition of concrete in highway structures. The study addressed the relevant technology, VDOT’s experience with each method, and advantages and disadvantages of use.

The following test methods were evaluated:

- ultrasonic shear-wave tomography
- ultrasonic pulse velocity
- crosshole sonic logging
- sonic echo–impulse response
- spectral analysis of surface waves
- impact echo scanner.

METHODS

Ultrasonic Shear-Wave Tomography

UST was evaluated for use on plain or reinforced concrete (Figure 1). As discussed earlier, UST is an ultrasonic pulse echo system that can provide real-time images (Edwards and Mason, 2011) based on measurements using ultrasonic shear-wave energy.

The UST device is equipped with an array of piezoceramic transducers that alternately send and receive low-frequency ultrasonic waves into a concrete test specimen. As the ultrasonic signal reflects off various elements within the concrete, the arrival times of the signal are measured and analyzed to reconstruct an image of the specimen interior. For this study, although a range of frequencies is available (25 to 85 kHz), UST was operated at 45 kHz. Scans may be performed at multiple points throughout an area of concrete and subsequently aggregated to form a 3D model of the concrete interior, revealing the locations of reinforcement, voids, and other distresses within by reflections (echoes) of the ultrasonic shear-wave pulse energy operated as a phased array.

VDOT tested the effectiveness of UST on a bonded concrete overlay on U.S. 58 in Virginia. The 24-year-old existing pavement consisted of 9-in-thick continuously reinforced concrete pavement with reinforcing steel at mid-depth and was overlaid with 4 in of plain concrete in August 2012. The particular section chosen for investigation had wide cracks—some

Figure 1. MIRA Ultrasonic Tomographer

exceeding 1 mm in width. An NDE of the pavement was conducted using UST to detect the full distressed area by exploring the distress boundaries and condition beneath the surface, which could include debonding of the overlay, delamination at the level of the steel, and voids in the concrete or around the steel. Cores were also taken to check the accuracy of UST.

UST's functionality enables it to perform a single scan as a "spot check" or multiple scans for mapping a section of the specimen interior. On Route 58, single scans were performed in areas with wide cracking to check for voids attributable to delamination or debonding and to determine the boundaries of the distressed areas. Then, multiple scans were taken to map the pavement in four areas that showed evidence of widespread distress at the surface (including closely spaced or intersecting cracks, faulting, and spalling) for a better understanding of the extent and severity of the distressed area. A fifth location with no evidence of damage was also scanned and mapped as a control area.

The associated software package with the UST device used includes a modeling program (IdealViewer) that was used to "stitch together" consecutive scans to form 3D volume renderings of the internal pavement structure, which then are tomographical models of the condition of the pavement (Germann Instruments, 2011).

Ultrasonic Pulse Velocity

UPV was performed in the laboratory in accordance with ASTM C597 (Standard Test Method for Pulse Velocity Through Concrete) (ASTM, 2009). For this study, transducers were placed on opposite sides of the concrete and the time required for the signal to transmit from one side to the other was measured. The velocity was calculated by dividing the sample length (distance between the two transducers) by the time required for the signal to travel this distance.

Crosshole Sonic Logging

CSL is a form of ultrasonic evaluation that has become a popular method for integrity testing in drilled shaft construction. The technology works by emitting an ultrasonic signal between transducers, one transmitting and the other receiving, that have been placed in tubes in the shafts. The time for the first signal to leave the transmitter and arrive at the receiver, known as first arrival time (FAT), is altered when the signal is travelling through irregularities, such as voids, in the concrete. These variations are tracked and analyzed by the CSL device, ultimately allowing inspectors to determine the location and magnitude of any change in FAT or velocity.

The use of this evaluation method involves attaching steel or polyvinyl chloride tubes with an inner diameter of about 2 in to the reinforcing steel and then placing this assembly in the shaft. Multiple tubes are used in each shaft, which are attached to the inside (typically) or outside (much less common) of the reinforcement cage. In large-diameter shafts, more tubes are added, with generally one tube being used per foot of shaft diameter with a minimum of two tubes. After the concrete has been placed and sets (typically tested at 3 to 7 days of age), the CSL transmitter and receiver are placed in the tubes and testing ensues in accordance with

ASTM D6760 (Standard Test Method for Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing) (ASTM, 2008).

The associated software (Olson Instruments, Inc., 2007) determines the FAT and associated average velocity of waves throughout the entire shaft depth based on the tube spacing and compares it to individual point velocities along the shaft. The analyzer looks for areas of “questionable” concrete, which are areas with a drop of 10% to 20% in wave velocity, or “poor” concrete, which are areas with a drop greater than 20%. Any area of weakness will manifest itself as a spike on a generated plot of velocity versus shaft depth. Irregularities also appear on plots of energy and arrival time versus shaft depth, because arrival time will increase and energy will decrease, as exemplified in Figures 2 and 3.

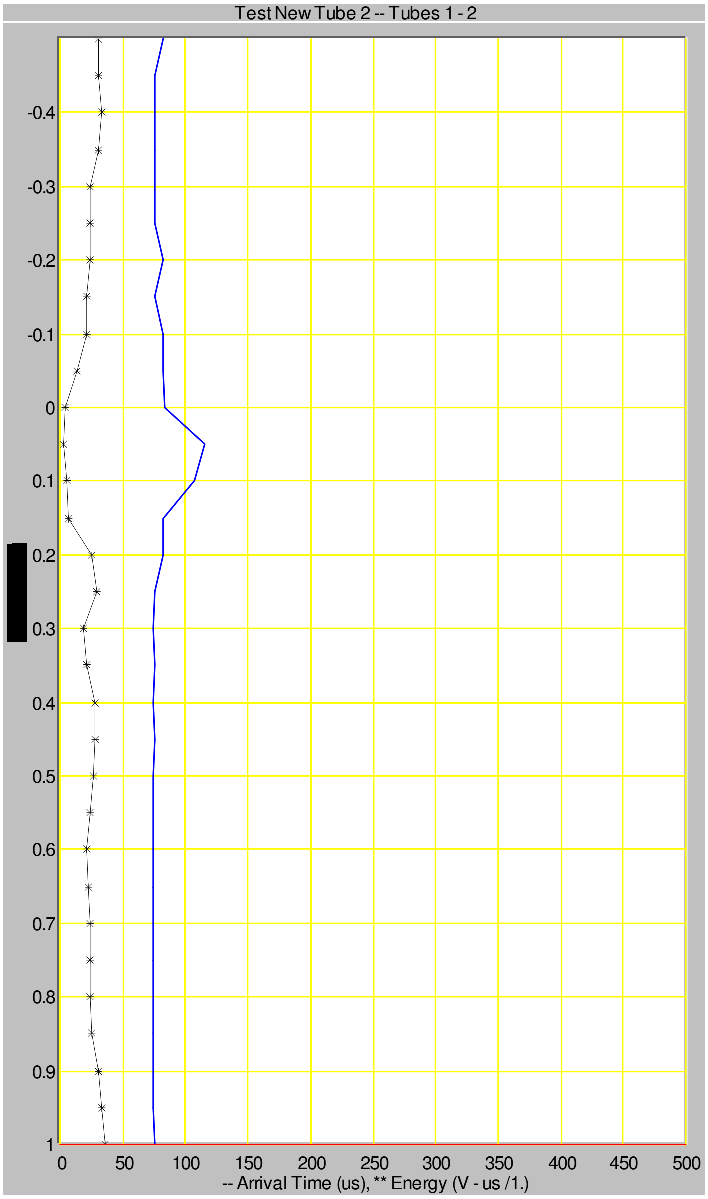

Figure 2. Crosshole Sonic Logging. Plots of arrival time (*solid line*) and energy (*dotted line*) versus shaft depth for a test specimen indicating a defect between the 0 and 0.1 ft mark.

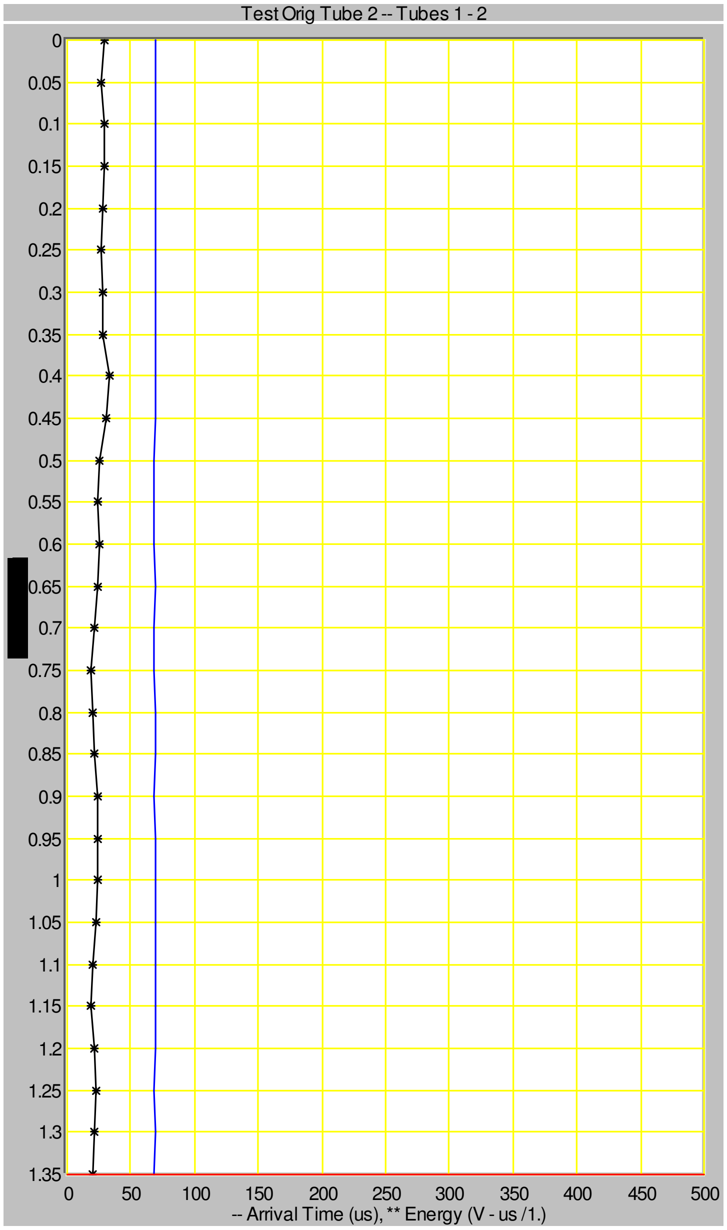

Figure 3. Crosshole Sonic Logging. Plots of arrival time (*solid line*) and energy (*dotted line*) versus shaft depth for a test specimen indicating no substantial voids.

CSL testing was performed at two test locations. The first was on drilled shafts supporting the bridge on Route 28 over Broad Run in Bristow in Prince William County, Virginia. The second was on test shafts placed at VDOT's Boyd Tavern Area Headquarters (AHQ).

The drilled shafts (with a diameter of 4 ft) were built for the adjacent northbound and southbound Route 28 bridges placed in 2006 and 2007, respectively. Each bridge required 24 shafts. Except for 12 shafts for the southbound bridge that used self-consolidating concrete (SCC), the shafts used conventional concrete. Four metal tubes of 2 in internal diameter were attached around the inside of the reinforcement cage in each shaft to allow for CSL testing after placement.

The CSL device was also evaluated for integrity testing in the test shafts at the Boyd Tavern AHQ. The test shafts were used specifically for the determination of the effectiveness of NDE methods, including CSL. Three shafts measuring 2 ft in diameter and 8 ft deep were drilled. In one shaft, the top 3 ft was an additional 1 ft in diameter to provide a larger cover depth. The reinforcement cages were designed to create voids in the concrete at known locations to determine the effectiveness of the device at void detection.

Concretes of different workability and quality were placed in these test shafts. Initially, the concrete had a conventional slump and was placed in the bottom 5 ft of the first shaft. Then, concrete was put in wheelbarrows and the water content was increased, which also increased the slump. This concrete with a higher water–cementitious material ratio was placed in the top portion of the first shaft. Then, high-range water-reducing admixture (HRWRA) was added to the concrete in the truck to make it SCC. The slump flow was measured. Finally, after the concrete had set, CSL measurements were made.

Sonic Echo–Impulse Response

SE/IR testing (ASTM D5882) (Standard Test Method for Low Strain Impact Integrity Testing of Deep Foundations) (ASTM, 2007) is a well-established and commonly used method for the NDE of concrete structures such as drilled shafts and driven piles and can also be used on thick elements such as abutments, piers, and tunnel walls of 6 ft or more where the similar IE resonance technique does not penetrate deeper. The SE/IR testing device works through the use of an impactor (typically a 3-lb impulse hammer that can measure the impact force with a hard plastic tip) to strike the structure, thereby sending stress waves of a designated velocity throughout the area of interest. These waves are then reflected off the bottom of the structure and received by a velocity transducer located at the surface. If the velocity and travel time of the wave are known, the distance traveled by the wave and thus the thickness of the structure can be determined.

Any voids or defects within the concrete will disrupt the wave travel, and as a result, the thickness at that point will appear different from undamaged areas of the structure. Comparing measured thicknesses to the known thickness of the structure allows defective areas to be identified easily. For clarity, it is important to mention that a similar testing approach can also be used to check for shallow delaminations, cracking damage, and voids in structural concrete/pavements; the technique is known as the slab impulse response (ASTM C1740) (ASTM, 2010) and is generally applicable to concrete 2 ft or less in thickness.

For this study, SE/IR was used for integrity testing of the drilled shafts at Boyd Tavern AHQ. The shafts were placed solely for the purpose of testing the performance of NDE methods in void detection. Researchers were interested in the effectiveness of SE/IR testing at detecting the depth and location of predetermined voids within the test shafts. The testing method and equipment are shown in Figure 4.

Figure 4. Sonic Echo–Impulse Response Testing at VDOT's Boyd Tavern Area Headquarters

Spectral Analysis of Surface Waves

SASW is a geophysical method that can be used to assess the internal condition of concrete structures. For this study, a BDS was used to generate the seismic wave that would be used for this type of NDE. A more in-depth description of how this device operates is provided by Tinkey et al. (2011, 2013), who also indicated favorable results in detecting delaminations in asphalt-overlaid concrete decks. In short, the primary focus of this portion of the study was on using SASW to evaluate differences in the elastic modulus of the concrete underneath an asphalt overlay.

The researchers and the developer of the BDS verbally agreed that VCTIR would validate the SASW technique by testing an asphalt-overlaid bridge with the BDS. After testing, the developer would evaluate the data and select several locations where the asphalt overlay would be removed and the underlying concrete exposed. This would be done to determine the effectiveness of the SASW scanning technology of the BDS.

For validation, SASW test scanning using the BDS was performed by the equipment developer on the southbound lane of the Mechums River Bridge near Free Union, Virginia (shown in Figure 5). The Mechums River Bridge is a four-span post-tensioned box beam bridge and has an asphalt overlay.

Impact Echo Scanner

Based on ASTM C1383 (Standard Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method) (ASTM, 2010b) and the stationary IE method, a hand-held IES was developed by an NDE equipment manufacturer. The IES uses a rolling displacement transducer assembly that incorporates multiple sensors (Tinkey and Olson,

Figure 5. Photograph of Bridge Deck Scanner. Impactor solenoids on sides of wheels and brass displacement transducers spaced every 6 in aligned for impact echo test and spectral analysis of surface waves test.

2007, 2008). This design change from the traditional stationary method uses an optocoupler on the central wheel that tracks the distance the IES has moved linearly. This feature permits the moving IE testing process and enables a more rapid mapping for voids and delaminations. Moreover, even though the presence of several mats of steel can have an influence on the data, this influence is not as deleterious as compared to the results when traditional ground-penetrating radar is used. The equipment was operated in accordance with the guidelines provided by the equipment manufacturer (Olson Instruments, Inc., 2007).

RESULTS AND DISCUSSION

Ultrasonic Shear-Wave Tomography

The UST model outputs were used to evaluate the level of pavement distress at the five test areas along Route 58. UST was found to be capable of detecting and modeling different levels of internal distress. For example, Figure 6 depicts a section view of an area of pavement that exhibits relatively little distress, as only the location of reinforcement is apparent in the scan.

Figure 7 depicts another section view generated by the UST software package but this time of an area of pavement with evidence of voids created by the delamination of concrete at the steel reinforcement level. These delaminations were later verified by a corresponding core from the same location, as shown in Figure 8.

Figure 9 exemplifies an isometric view of the pavement structure taken at an area of high distress; in this case, the entire area contained debonded overlay.

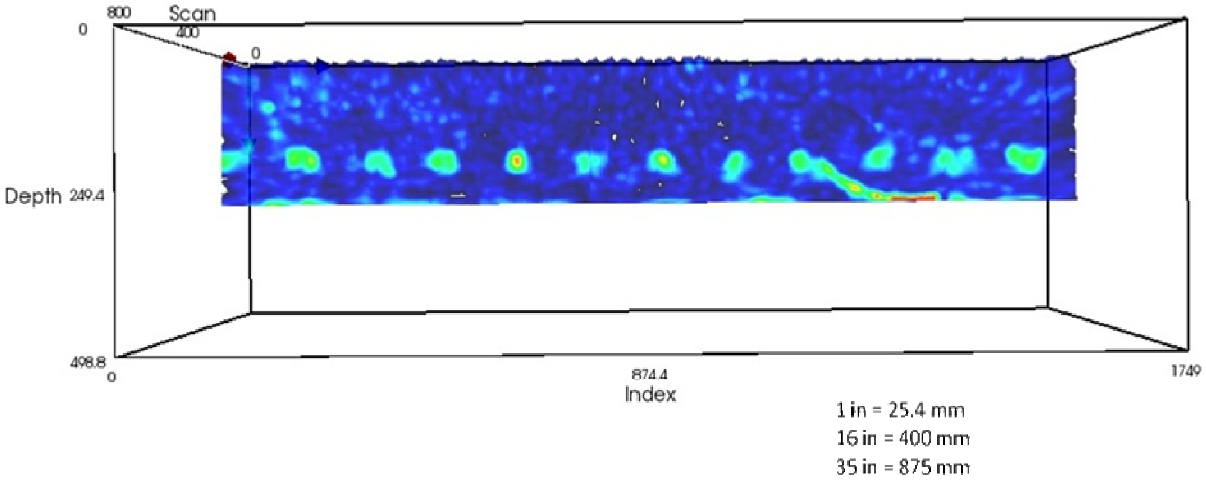

Figure 6. UST Section View of Little Distress (blue/green in color image; lighter gray in grayscale)

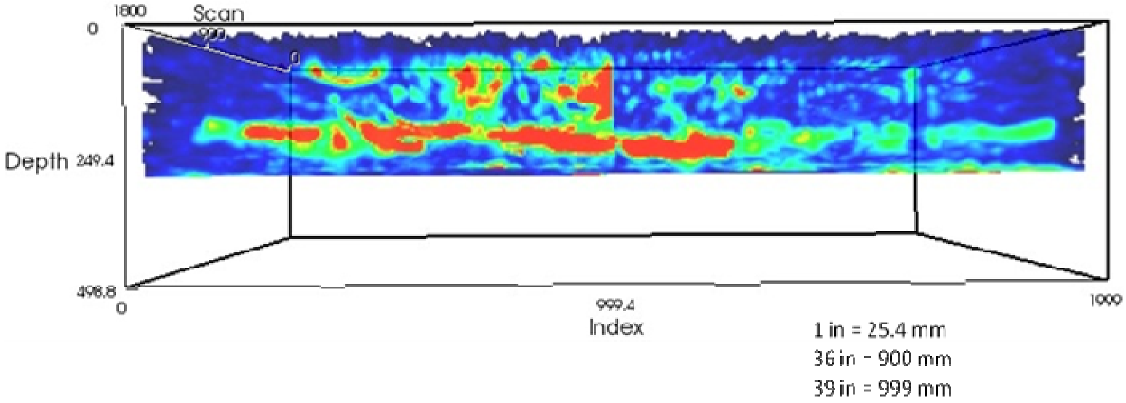

Figure 7. UST Section View of Delamination (red/yellow in color image; slightly darker gray encapsulated by light gray in grayscale)

Figure 8. Actual Core Associated With Figure 7 Confirming Predicted Delamination

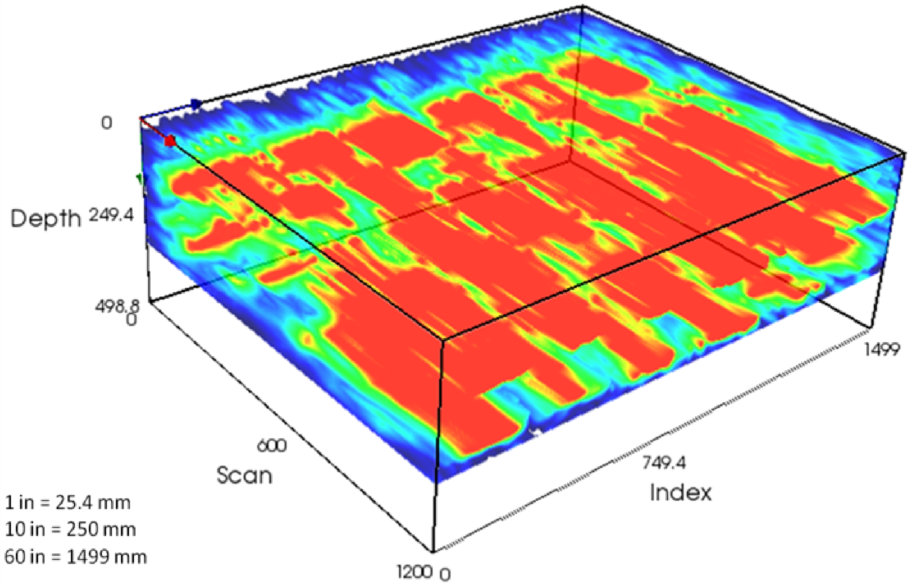

Figure 9. UST Isometric View of Debonded Overlay (red/yellow in color image; slightly darker gray encapsulated by light gray in grayscale)

The scans exemplify UST's effectiveness at determining the internal conditions of concrete structures, regardless of whether they are of low, medium, or high distress. Physical cores taken from the test areas verified these results. Further, it is clear that the software package produces images that are easily understood, with multiple viewpoints that allow for complete visualization of the structure. Thus, UST should be considered a valuable means of NDE for concrete structures. However, it is important to recognize that the detection depth is limited, although the detection limit was not evaluated as a part of this study. Another issue is whether UST can detect incipient distresses. For example, an incipient separation or crack still with contacts in many points cannot be detected. It appears that major distresses are discernible; however, incipient ones are not.

Ultrasonic Pulse Velocity

A comparison of two UPV systems, shown in Figure 10, revealed variability between the two systems, especially with regard to higher strength samples. The difference in velocity is attributed to the difference in the sensitivity of the equipment, which does not appear to be as large at the lower limit of the strength where both devices show similar results. This strong overlap is in the region of the graph that is above the 28-day acceptance minimum value of 4.000 psi. Therefore, both devices would give similar responses in this region; however, it would be interesting to evaluate the response in a follow-up research project of the two devices for concrete specimens with strengths below 4,000 psi.

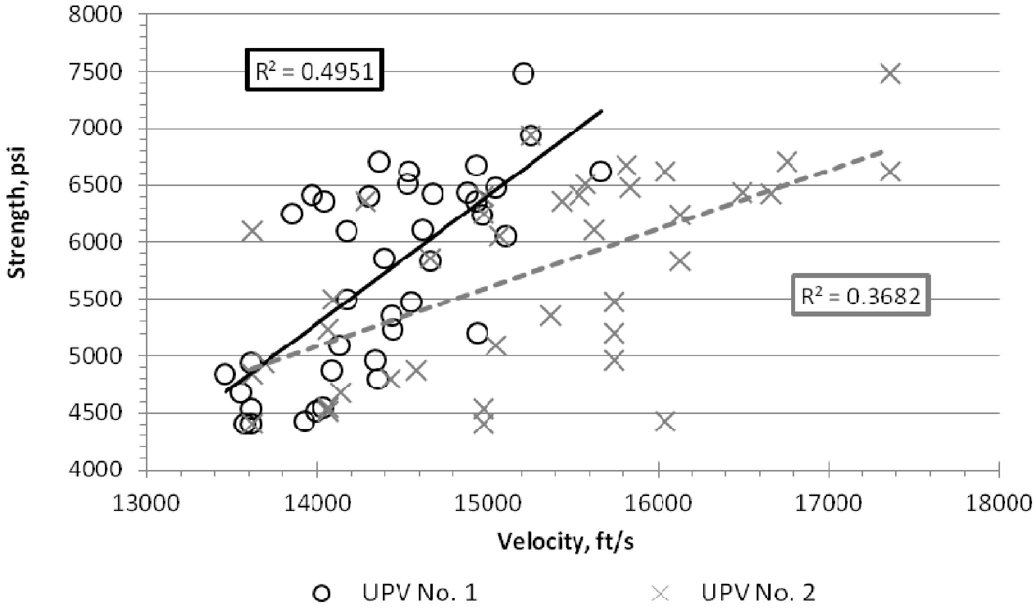

Figure 10. Comparison of Velocities for Two Ultrasonic Pulse Velocity (UPV) Devices. Trend lines and R^2 values are based on linear best fits.

Crosshole Sonic Logging

The results of the CSL evaluation showed that the velocities along the entirety of each shaft were relatively consistent. Despite the existence of minor fluctuations, no shafts exhibited variations large enough to suggest the existence of questionable concrete. These data were used further to compare SCC concrete to conventional concrete. Plots of velocity versus depth for SCC and conventional concrete are provided in Figures 11 and 12, respectively. Figure 11 also includes an example of the FAT plus energy plot, which is another way of viewing the data that can provide insight into the condition of the concrete in the drilled shaft.

CSL was also found effective at determining the relative strength of the concrete in different areas of a shaft—the higher the velocity, the more dense the concrete. The device recorded higher sonic velocities near the bottom of the shaft and lower velocities near the top, which was consistent with the varying quality concrete purposefully placed in the shafts. These results are summarized in Figure 13. This provides evidence of a common problem in drilled shaft construction. The water at the bottom will be pushed to the top during tremie or pumping operations and provide a weak surface layer unless this original weak layer is displaced by more concrete in the shaft.

The results of these two studies suggest that CSL is a valid form of integrity testing for drilled shafts. It was shown that this technology is able to detect voids arising as a result of poor consolidation as well as weak areas that may result from the concrete mixing with groundwater or surrounding soil in the shaft. Limitations of CSL include the fact that the test monitors the integrity of the concrete only within the reinforcement cage; no information can be determined about the quality of the rebar cover that surrounds the transmitters and receivers. Further, CSL requires the embedding of access tubes within the shaft, which implies additional labor and expense. Finally, tests can be performed only so long as the top of the shaft remains uncovered because once the shaft is capped, data can no longer be collected. Despite these disadvantages, CSL remains an extremely useful evaluation method for drilled shafts because of the wealth and accuracy of information obtained about the concrete's integrity, even far below the ground surface.

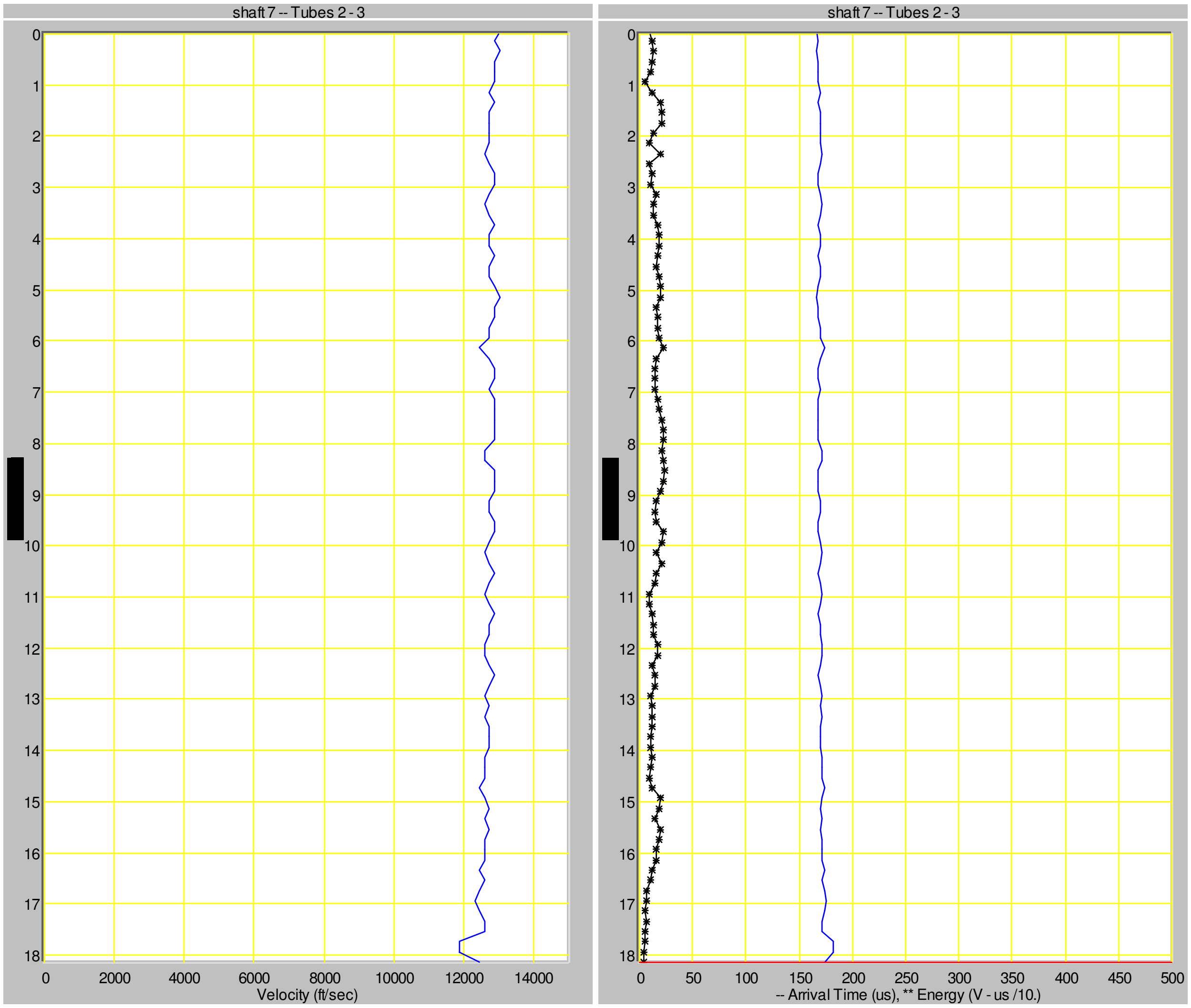

Figure 11. Example Velocity Plot (*Left*) and First Interval Time Plus Energy Plot (R*ight*) for Self-Consolidating Concrete

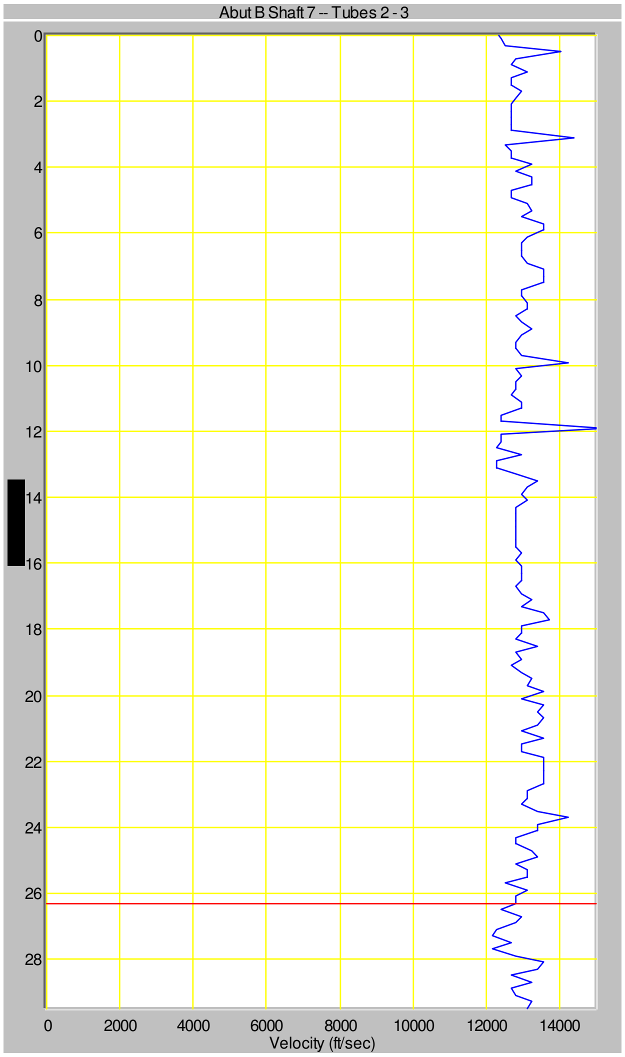

Figure 12. Example Velocity Plot for Conventional Concrete

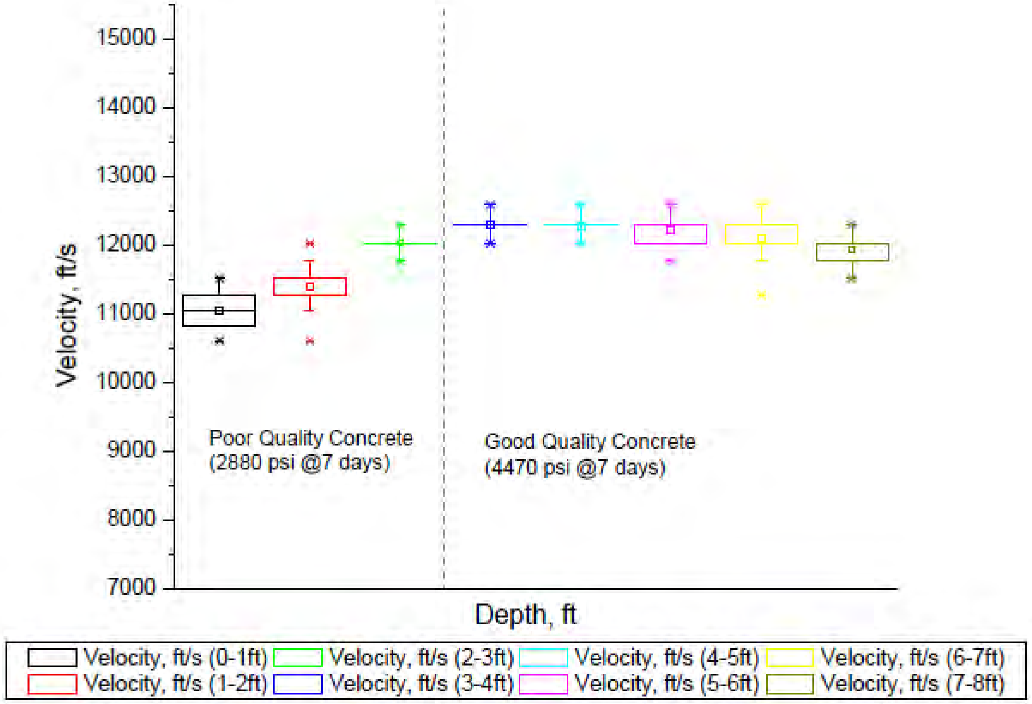

Figure 13. Comparison of Compressive Strength and Measured Velocity in Two Shaft Sections

Sonic Echo–Impulse Response

SE/IR testing was reliable in the detection of voids but was not always able to establish a precise location. This was due to a variation in the measurement of void and overall shaft depth that depended on the designated wave velocity of the SE/IR unit. As the selected wave velocity increased, the measured shaft and void depth increased, as seen in Table 1. Although the device was able to find the relative location of the void within the shaft in every case, the precise location was correctly identified only at 10,000 ft/sec. This illustrates the importance of care in the selection of signal velocity in SE/IR testing—the appropriate choice will vary depending on the specific project. If SE/IR uses the velocity from the UPV, a better estimate of the location of distress will be found. These trials also demonstrate the benefit of SE/IR over some techniques when access to a structural element is limited. Pailes et al. (2010) demonstrated this in other VCTIR research where SE/IR was used to assess the condition of piles in an existing structure. In that study, the piles were evaluated even with a pile cap connecting all of the piles in a bent and limiting access to the top of the pile.

Table 1. Influence of Different Velocity Values on Feature Depth

	Calculated Depth, ft				
Description	**For Velocity = 9,000 ft/sec**	**For Velocity = 10,000 ft/sec**	**For Velocity = 11,000 ft/sec**	**For Velocity = 12,000 ft/sec**	**For Velocity = 13,000 ft/sec**
Void location	3.7	4.1	4.5	4.9	5.3
Shaft length	7.5	8.4	9.2	10.0	10.9

Although, as discussed, SE/IR has been shown to be a quick and inexpensive test for evaluating the voids and delaminations in drilled shafts, the technology has shortcomings, including inaccuracy that can occur in measuring the location of defects, a higher likelihood of false positives, and the potential to miss voids in the concrete that are obscured by other defects. Further, in drilled shaft construction specifically, SE/IR testing has been found to be ineffective as depths become too great relative to the diameter of the element. SE/IR has been shown to be limited to foundations with "length-to-diameter ratios of up to 20:1" because of attenuation of the wave energy, although "higher ratios (30:1) are possible in softer soils" (Federal Lands Highway Program, 2013). It is evident that some of these shortcomings can be overcome by combining the technique with other techniques, such as UPV, to determine wave speed or CSL to identify obscured defects. Regardless of these issues, SE/IR is useful for a quick, initial evaluation of a structure by identifying potentially defective areas that warrant further investigation.

Surface Analysis of Spectral Waves

The SASW analysis identified potential locations of poor concrete within the bridge that were not identifiable from visible observation. Four locations on the bridge were selected by the BDS designer for further inspection through visual confirmation by removing asphalt sections to confirm the SASW results. The proposed sections to be removed were overlaid on the SASW results and are shown in Figure 14. Of the four identified test locations, two "bad," one "intermediate," and one "good" area of the bridge were further inspected.

The asphalt overlay in four locations of varying distress levels, with the findings documented in Table 2, was removed to expose the top of the box beams, which included two keyway locations. Several observations made upon removal of the overlay and images of each location are shown in Figures 15 through 18. The findings indicated that debonding of the epoxy over the box beams, and possible lower strength of keyway grout, was the source of the distress instead of the actual concrete damage. In each of the four observed locations, the concrete observed was in good condition with no visible deterioration. However, it was also clear that water infiltration under the asphalt overlay (Figure 19) and into the keyway was occurring, with regions lacking epoxy evident. Both of the cases exhibiting the worst level of distress according to the SASW results exhibited moisture in either the concrete or grout. It was also clear from the underside of the bridge that moisture was penetrating the asphalt overlay, membrane, and box beams, with the onset of corrosion occurring (Figures 20 through 22). Unfortunately, distressed areas on beams and keyways were not validated since the box beams were not cored because of concerns regarding damaging the beams. However, deterioration of the keyway was most probable based on observations of moisture penetrating under the membrane, which then flowed between the beams to the underside of the bridge.

Upon completion of the assessment, the removed asphalt was replaced through placing a tack coat on the box beam and surrounding cut asphalt surfaces and then filling each location with a proprietary water-activated patching material. The patching material was then compacted and activated with water, and then shortly after the repair was finished, it was ready for traffic.

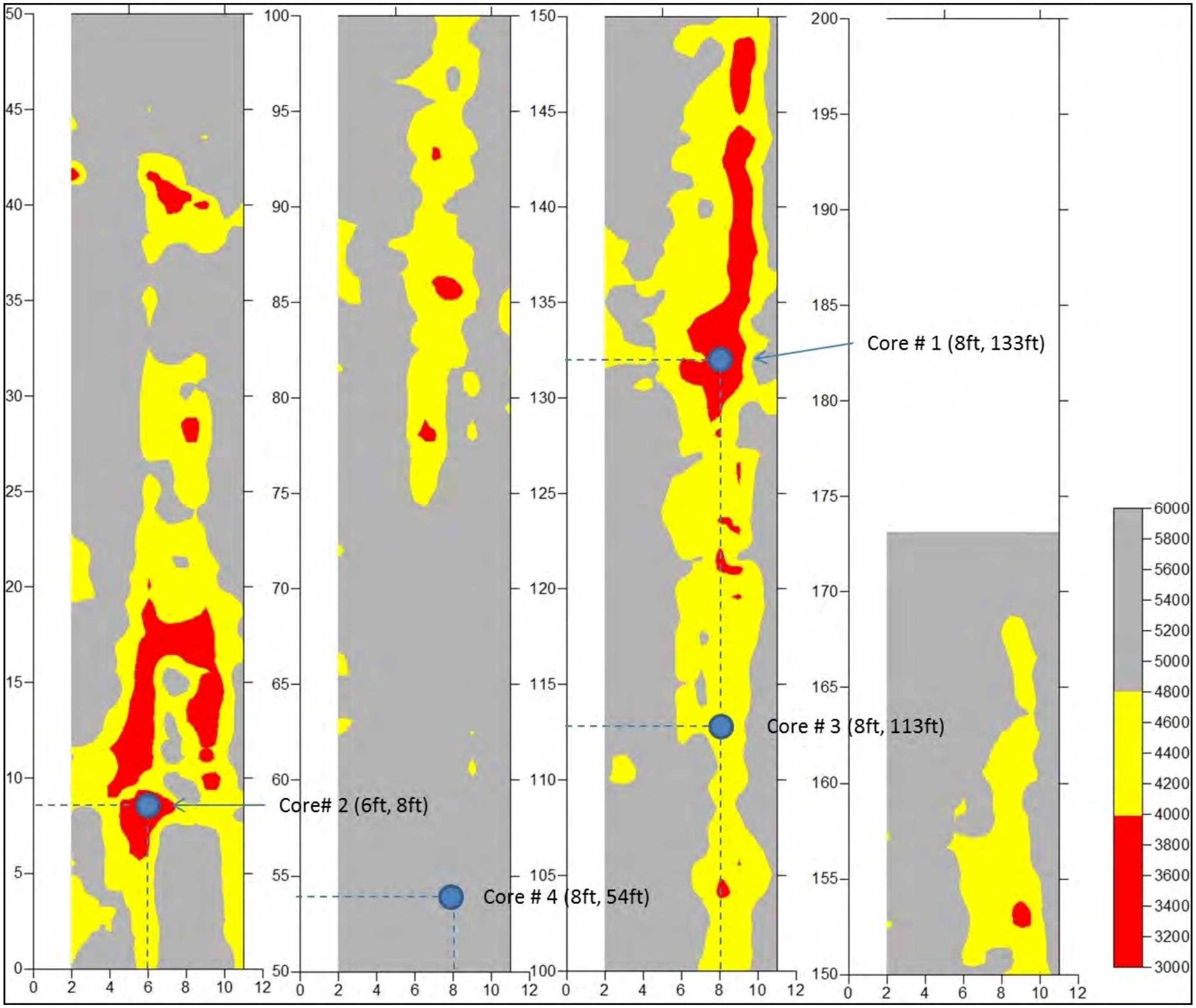

Figure 14. Illustration of Results of Spectral Analysis of Surface Waves. Designated locations, indicated as core numbers, are overlaid (surface wave velocity scale in ft/sec on *right*) (poor responses are yellow/red in color and lightest/darkest gray in grayscale). Gray in the color version indicates sound concrete.

Table 2. Summary of Observations From Mechums River Bridge

Description	**Core Location 1 (Figure 15)**	**Core Location 2 (Figure 16)**	**Core Location 3 (Figure 17)**	**Core Location 4 (Figure 18)**
Expected level of distress	Worst	Worst	Intermediate	None
Size of asphalt opening	12 in by 24 in	12 in by 12 in	12 in by 12 in	12 in by 12 in
Asphalt thickness	2.75 in	2.75 in	2.75 in	2.75 in
Asphalt condition	Dry	Dry	Dry	1 in moisture into asphalt
Concrete condition	Dry	Moist	Dry	Dry
Keyway grout condition	• Grout wet • Grout weaker than surrounding concrete	• Grout in good condition • Grout weaker than surrounding concrete	No comment	No comment
Epoxy condition	• Epoxy debonded from box beam • No epoxy on keyway	• Epoxy debonded from box beam • No epoxy on keyway	Epoxy not sticking to box beams well	Epoxy well bonded
Impact echo on concrete	• Velocity 12,000 ft/sec • Indicates 4 in and 4.7 in, 4 in and 5.9 in thick	No comment	Indicates 4.9 in to 5.5 in thick	Indicates 4.57 in, 4.58 in, 5.2 in thick
Impact echo on asphalt	Poor echo	No comment	Showing 8 in thick	Poor echo

Figure 15. Asphalt Removed at Location 1

Figure 16. Asphalt Removed at Location 2

Figure 17. Asphalt Removed at Location 3

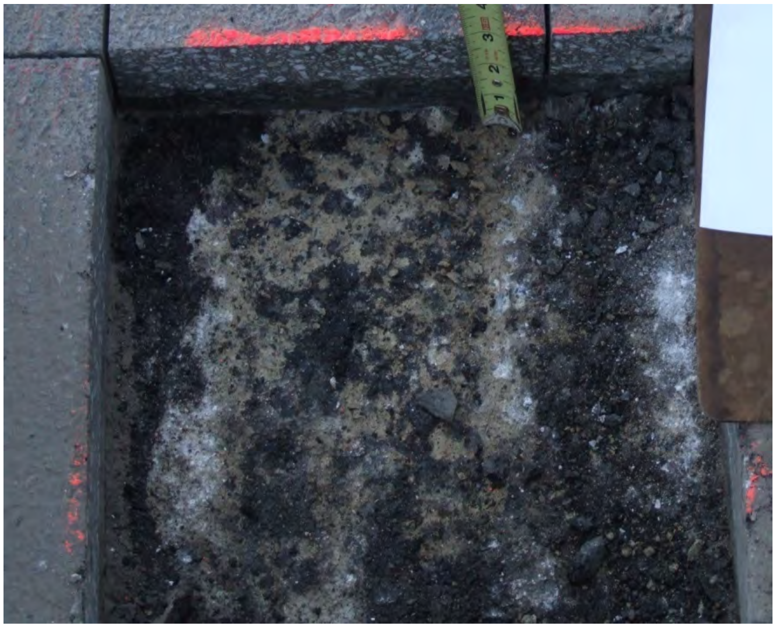

Figure 18. Asphalt Removed at Location 4

Figure 19. Asphalt at Location 4 Showing 1-in of Moisture Along Bottom, Which Was Adjacent to Overlay

Figure 20. Result of Moisture Penetrating Between Two Box Beams

Figure 21. Evident Moisture Penetration on Abutment

Figure 22. Evident Corrosion Along Bottom of Pier Cap Initiating Spalling of the Concrete

Impact Echo Scanner

The IES, similar to IE, is used to determine the presence of voids and delaminations in reinforced concrete on the basis that both of these defects create a transition in materials (concrete to air). Initially, work with the IES focused on using it to determine if consolidation was adequate around the reinforcing steel in concrete parapets (Figure 23). The IES had difficulties performing this task of identifying voids, which was attributed to the roughened surface broom finish (Figure 24). Subsequent work to detect delaminations on reinforced concrete elements with smoother form-finished surfaces showed more favorable results. IES scans on the form-finished box beam surface (Figure 25) provided useful information on the degree of delamination present on two box beams, Beams 8 and 9, as shown in Figures 26 through 29. In Figures 26 and 27, damage is apparent in the 2.5-ft region for Beam 8; in Figures 28 and 29, damage is occurring at the two ends of Beam 9 (first 2.5 ft and last 2 ft of scan).

This finding was followed up with a separate research effort that studied the influence of different surface conditions on IES measurements and demonstrated that if surface conditions were acceptable, valuable information could be extracted from cast concrete elements (Lewis and Sharp, 2013). This work demonstrated that the IES, although not applicable for every application, can offer benefits for use in the field as long as the surface of the concrete is suitable.

Figure 23. Use of Impact Echo Scanner on Parapet

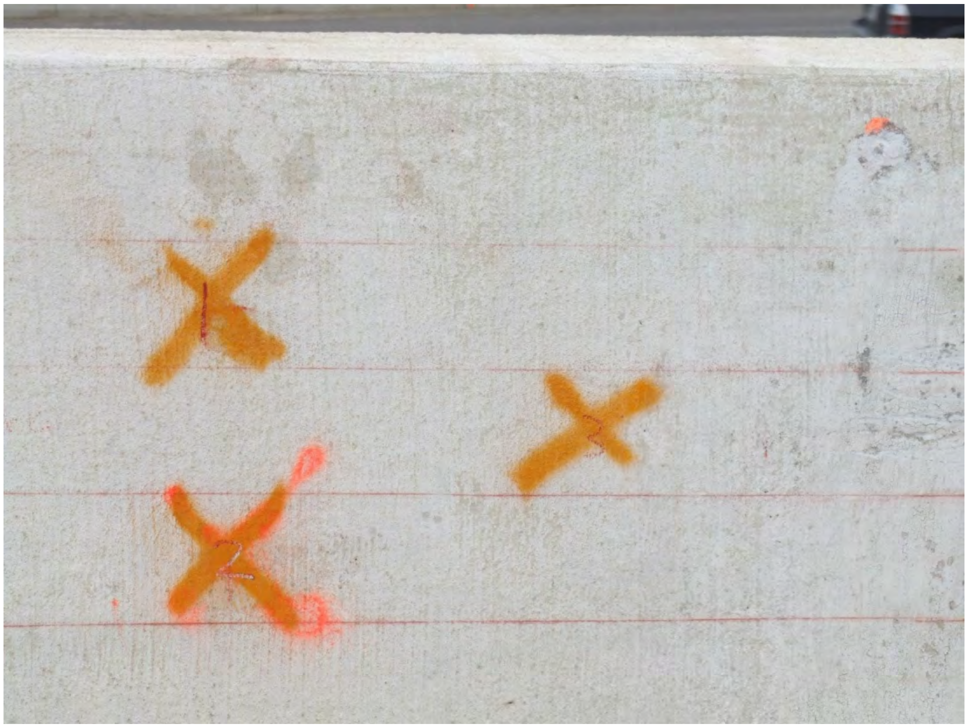

Figure 24. Broom Finish on Parapet

Figure 25. Bottom Side of Box Beams Showing Smooth Finish That Is Ideal for Use of Impact Echo Scanner

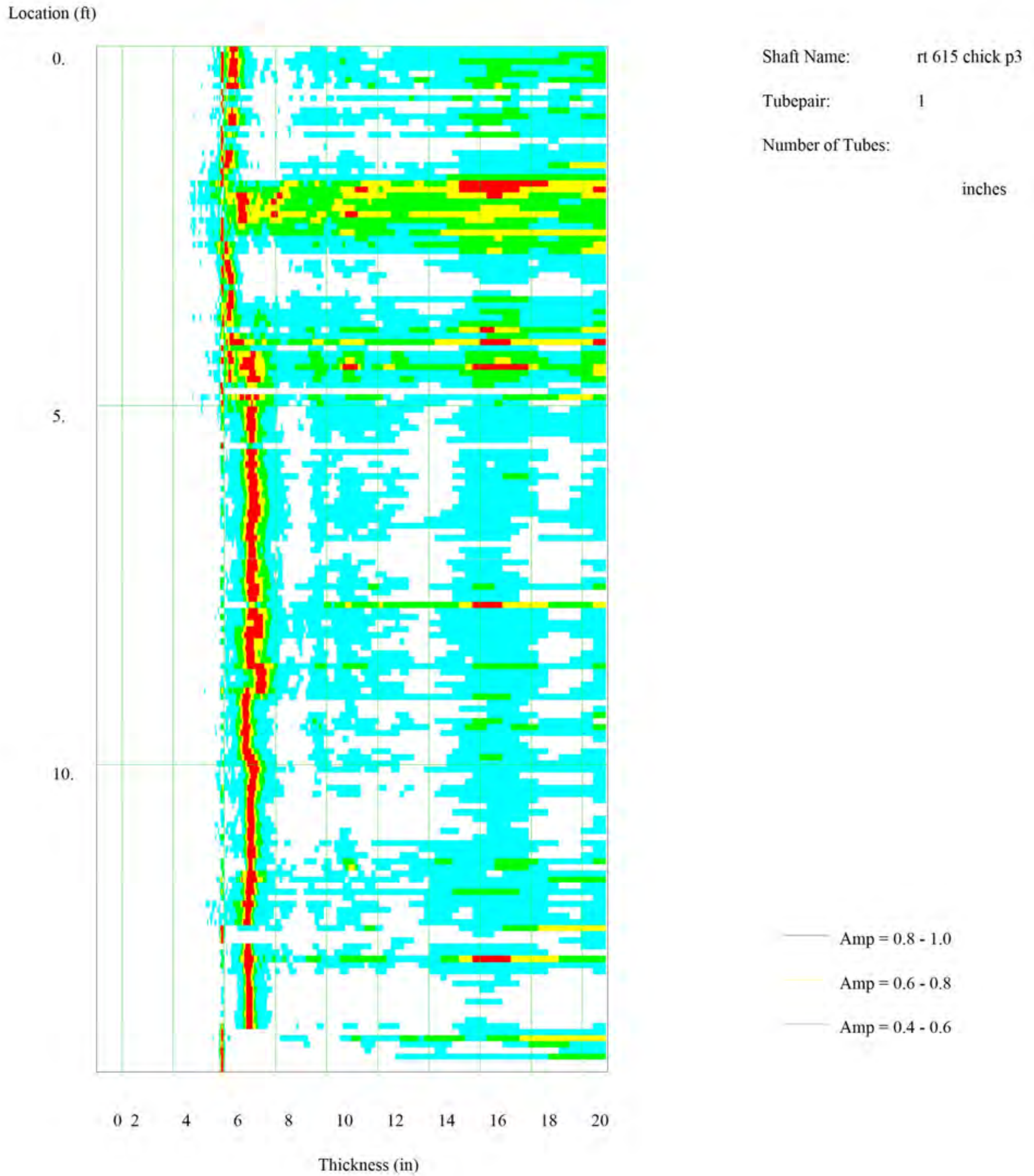

Figure 26. Impact Echo Scanner Results, Beam 8, Line 1, Indicating Damage at About 2.5 ft and 4.5 ft

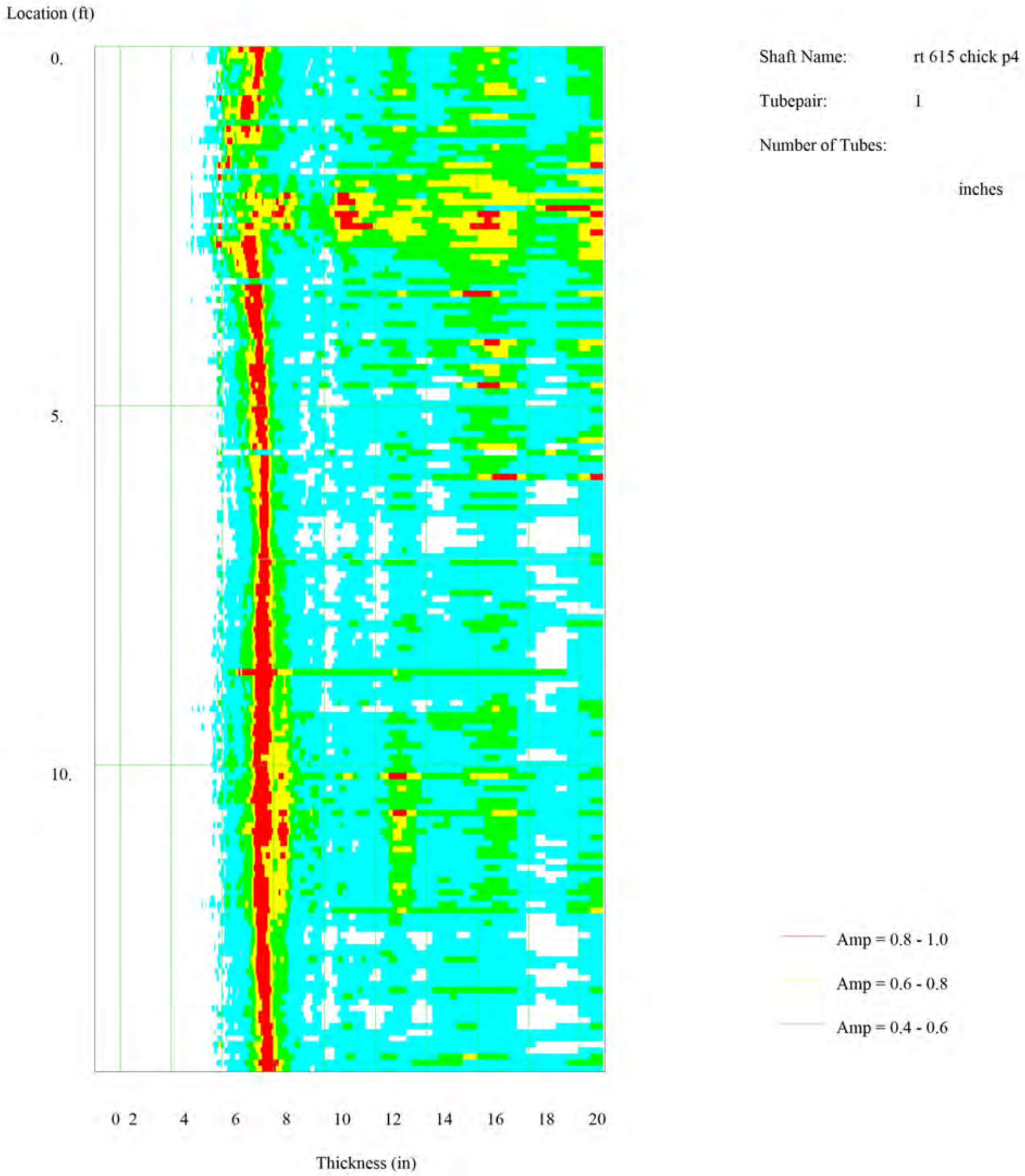

Figure 27. Impact Echo Scanner Results, Beam 8, Line 3, Indicating Damage at About 2.5 ft

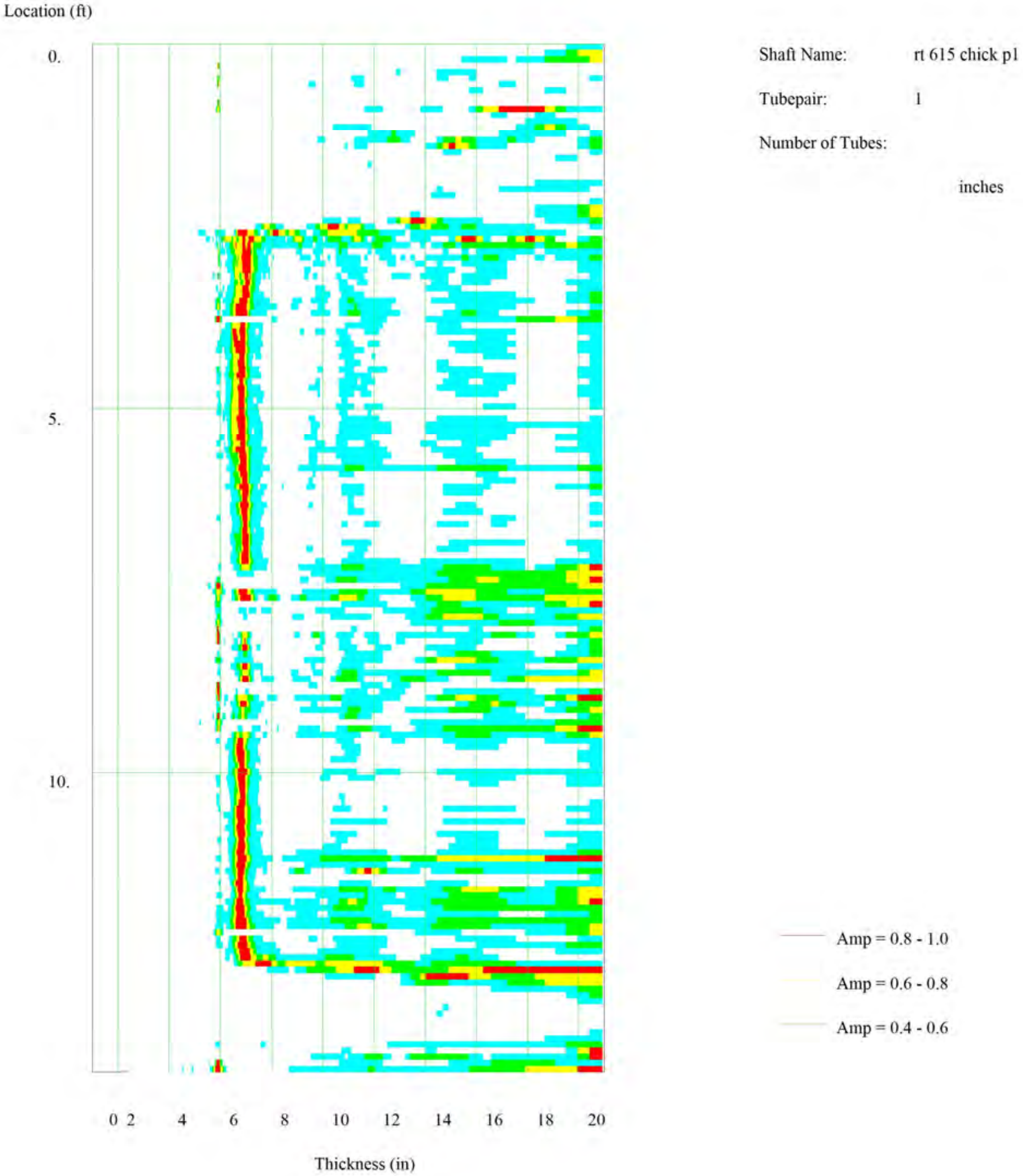

Figure 28. Impact Echo Scanner Results, Beam 9, Line 1, Indicating Damage at First 2.5 ft and Last 2 ft

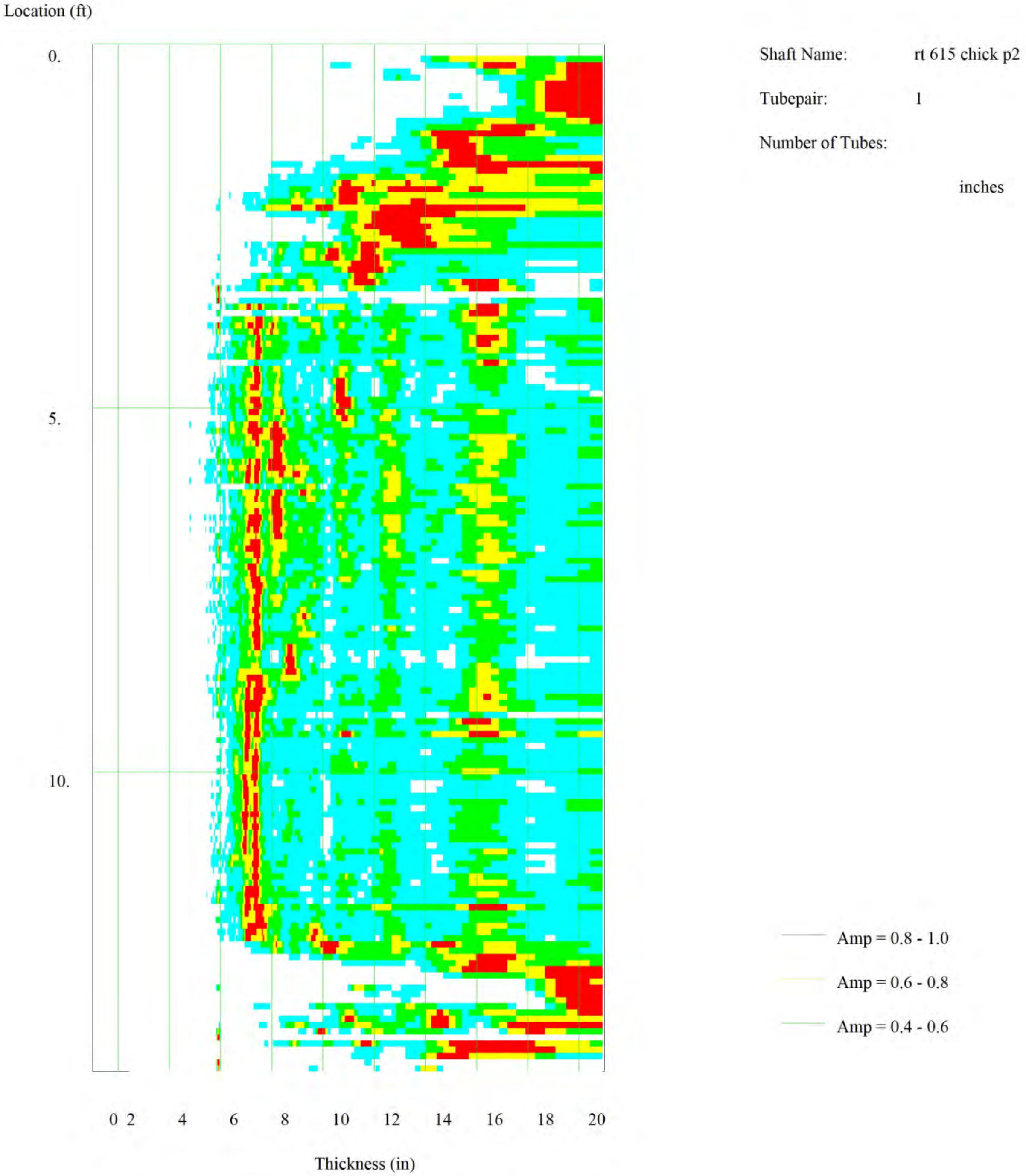

Figure 29. Impact Echo Scanner Results, Beam 9, Line 3, Indicating Damage at First 2.5 ft and Last 2 ft

End-Result Specifications

VDOT is developing ERS that transfer the responsibility of developing mixtures to the contractor. In this role, the contractor designs the mixtures and submits data showing compliance with the specifications (Ozyildirim, 2011). At the fresh state, concrete is tested for air content, slump, density, and temperature. In the hardened state, concrete is tested for strength and permeability using cylinders (Ozyildirim, 2011).

The mechanical wave methods can be used successfully to test concrete in the hardened state to determine if the concrete furnished is of the quality desired. In ERS, to determine the variability of the material, many (at least three) samples would be tested (Ozyildirim, 2011). If a control concrete were available, the new concretes could be compared to the control concrete using NDE. Sonic tests such as the pulse velocity and SE/IR could be applied to determine if the concrete is of the quality desired. In the future, ERS could also include in-place parameters such as the thickness, voids, cover depth, and the delaminations that can be evaluated using the various wave techniques.

CONCLUSIONS

General

- *Many of the NDE techniques evaluated in this study can provide VDOT with tools to ensure that concrete in new construction complies with VDOT specifications and to evaluate the health of existing structures.*

- *The use of five of the NDE techniques evaluated (i.e., UST, UPV, CSL, SE/IR, and the IES) could improve the effectiveness of an ERS program to determine compliance with specifications in terms of concrete quality, thickness, and the condition of defects without damaging the structure. Use of the sixth NDE technique evaluated, i.e., SASW with the BDS, also shows promise, but additional validation is required to conclude with certainty that this method should be used.*

Ultrasonic Shear-Wave Tomography

- *UST can be successfully used in determining the major distressed areas in pavements.*

Ultrasonic Pulse Velocity

- *UPV can be used to determine the wave velocity in a concrete element that is tested using SE/IR.*

- *UPV can also be used for assessing differences in concrete quality.*

Crosshole Sonic Logging

- *CSL can detect voids between the tubes in drilled shafts. It can also be an indicator of concrete performance and quality.*

Sonic Echo–Impulse Response

- *SE/IR is reliable in the detection of voids but is not always able to establish a precise location because of the selection of the wave velocity. UPV can be used in conjunction with SE/IR to improve the estimated wave velocity.*

- *With SE/IR, the detectable depth can be limited by the width of the element being evaluated. SE/IR can also determine thickness.*

- *SE/IR can be used in conjunction with CSL to improve the detection of defects in concrete foundations.*

- *SE/IR provides information on cover depth that is lacking in CSL analysis.*

- *SE/IR may miss multiple defects that are located at different elevations since an upper defect shields the wave from reaching and reflecting from a lower defect.*

Spectral Analysis of Surface Waves

- *SASW can identify locations of debonded epoxy between the asphalt overlay and the concrete box beams.*

- *The ability of SASW to identify distressed areas on beams and keyways was not validated, although deterioration of the keyway was likely; the box beams were not cored in order to prevent possible damage to the beams.*

Impact Echo Scanner

- *The IES can detect delaminations on smoother concrete surfaces (e.g., formed surfaces).*

RECOMMENDATIONS

1. *VDOT's Materials Division should consider using UST, CSL, SE/IR, UPV, and the IES to ensure compliance of concrete with the specifications in new construction and to evaluate the health of existing structures.*

2. *VDOT's Materials Division should acquire a UST device and use UST to detect major distressed areas in reinforced structures.*

3. *VDOT's Structure and Bridge Division should consider using SE/IR and UPV in conjunction with CSL when evaluating drilled shafts.*

4. *VCTIR should identify a candidate structure for SASW testing with the BDS system to validate this promising technique.*

5. *VCTIR should periodically sponsor a workshop and invite individuals from VDOT's Materials Division and the Federal Highway Administration's Nondestructive Evaluation Laboratory to improve and expedite the implementation of NDE techniques at VDOT.*

BENEFITS AND IMPLEMENTATION PROSPECTS

This study showed that nondestructive mechanical wave methods can be successfully used in determining concrete quality and the extent of distress in concrete structures. The next step is for VDOT/VCTIR to purchase MIRA and train people in the field to use the UST, CSL, SE/IR, and IES equipment to collect data on pavements and bridge structures. SASW with the BDS along with IE should be performed on an asphalt-overlaid bridge deck and a bare concrete deck with known top and bottom delaminations to validate this promising technique.

ACKNOWLEDGMENTS

The authors recognize the contributions of Cesar Apusen, Michael Burton, Lance Dougald, Kelley Frank, Jose Gomez, Jimmy Holland, Larry Lundy, Rodolfo Maruri, Taylor Moore, Larry Olson, Arthur Ordel, Michael Sprinkel, Jonathan Tanks, and Yajai Tinkey.

REFERENCES

ASTM International. ASTM D5882: Standard Test Method for Low Strain Impact Integrity Testing of Deep Foundations. In *Annual Book of ASTM Standards, Vol. 04.09: Soil and Rock (II).* West Conshohocken, PA, 2007.

ASTM International. ASTM D6760: Standard Test Method for Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing. In *Annual Book of ASTM Standards, Vol. 04.09: Soil and Rock (II).* West Conshohocken, PA, 2008.

ASTM International. ASTM C597: Standard Test Method for Pulse Velocity Through Concrete. In *Annual Book of ASTM Standards, Vol. 4.02: Concrete and Aggregates.* West Conshohocken, PA, 2009.

ASTM International. ASTM C1740: Standard Practice for Evaluating the Condition of Concrete Plates Using the Impulse-Response Method. In *Annual Book of ASTM Standards, Vol. 4.02: Concrete and Aggregates.* West Conshohocken, PA, 2010a.

ASTM International. ASTM C1383: Standard Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates,* West Conshohocken, Pa., 2010b.

Edwards, L., and Mason, Q. *Evaluation of Nondestructive Methods for Determining Pavement Thickness.* ERDC/GSL TR-11-41. U.S. Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS, 2011.

Federal Lands Highway Program. Surface Nondestructive Test (NDT) Methods. 2013. http://www.cflhd.gov/resources/agm/engApplications/BridgeSystemSubstructure/211SurfaceNDTMethods.cfm. Accessed November 30, 2013.

Germann Instruments. *MIRA Low-Frequency Ultrasonic Tomographer Operation Manual.* Evanston, IL, 2011.

Hoegh, K., Khazanovich, L., and Yu, H.T. Ultrasonic Tomography Technique for Evaluation of Concrete Pavements. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 2232. Transportation Research Board of the National Academies, Washington, DC, 2011, pp. 85-94.

Lewis, K.G., and Sharp, S.R. Application of Impact Echo Scanning for Void Detection on Concrete Test Beams That Replicate Different Surface Finishes. Presented at the 92nd Annual Meeting of the Transportation Research Board, Washington, DC, January 2013.

Lucas, J.L., Cousins, T.E., Brown, M.C., Lane, D. S., and Sharp, S.R. *Structural Load Testing and Flexure Analysis of the Route 701 Bridge in Louisa County, Virginia.* VTRC 04-R12. Virginia Transportation Research Council, Charlottesville, 2004.

Olson Instruments, Inc. *System Reference Manual 2007: Impact Echo Scanning.* Wheat Ridge, CO, 2007.

Ozyildirim, C. *End-Result Specifications for Hydraulic Cement Concrete: Phase II.* VCTIR 12-R2. Virginia Center for Transportation Innovation and Research, Charlottesville, 2011.

Pailes, B.M., Brown, M.C., and Sharp, S.R. *Condition Assessment and Determination of Methods for Evaluating Corrosion Damage in Piles Encapsulated in Protective Jackets on the Hampton Roads Bridge-Tunnel.* VTRC 10-R13. Virginia Transportation Research Council, Charlottesville, 2010.

Tinkey, Y., and Olson, L. Sensitivity Studies of Grout Defects in Posttensioned Bridge Ducts Using Impact Echo and Scanning Method. In *Transportation Research Record: Journal* *of the Transportation Research Board,* No. 2028. Transportation Research Board of the National Academies, Washington, DC, 2007, pp. 154-162.

Tinkey, Y., and Olson, L. Applications and Limitations of Impact-Echo Scanning for Void Detection in Posttensioned Bridge Ducts. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 2070. Transportation Research Board of the National Academies, Washington, DC, 2008, pp. 8-12.

Tinkey, Y., Olson, L.D., Miller, P., and Hergert, M. Advances in Stress Wave Scanning of Decks and Pavements. Presented at the Engineering Mechanics Institute Conference, Northeastern University, Boston, June 2-4, 2011.

Tinkey, Y., Miller, P., Leonard, M., Pott, A., and Olson, L. Bridge Deck Scanning for Condition Assessment of Bare Concrete and Asphalt Overlaid Decks. In *Transportation Research Board Annual 2013 Proceedings (CD).* Transportation Research Board of the National Academies, Washington, DC, January 2013.