Advances in Stress Wave Scanning of Decks and Pavements

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ABSTRACT

This paper discusses the application and benefits of new technology in providing the next generation of comprehensive condition evaluation of decks and asphalt pavements using stress wave scanning. The Vehicle-Mounted Bridge Deck Scanner (BDS) was funded by the NCHRP-IDEA program. The objective of the research project was to develop a Bridge Deck Scanner (BDS) that can be mounted behind any vehicle for comprehensive condition evaluation of concrete bridge decks with nondestructive evaluation (NDE) methods including Impact Echo (IE), Spectral Analysis of Surface Waves (SASW) and Automated Sounding (AS). The BDS performed all three nondestructive evaluation methods simultaneously with a test resolution of up to 0.5 ft along a scan line with a slow-rolling speed of 1 – 1.5 mph (1.6 – 2.4 km/hour). The objective of the BDS is to provide information on top and bottom delaminations, internal cracks, vertical crack depths, thickness profile, and the concrete quality/integrity and it was evaluated on bare concrete decks with excellent results.

The BDS was further researched and developed as part of a SHRP 2 project for detection of delaminated (debonded) asphalt pavement layers being conducted by the National Center for Asphalt Technology (NCAT) at Auburn University. Research was conducted on an initial blind basis by Olson Engineering of an asphalt pavement test section with debonded asphalt layers from shallow to greater depths. Based on the promising results, further research and development was conducted to expand the BDS system from one pair of scanning wheels to 3 pairs. The expanded BDS was then tested again at the NCAT track and the debonded asphalt areas were detected with very good accuracy. The expanded BDS system was then used on actual delaminated asphalt highway pavement sections in Florida and Kansas to evaluate the performance of the system and further improve it for detecting debonded asphalt conditions.

INTRODUCTION

Most of the conventionally reinforced concrete bridges in the nation were built between 1955 and 1970 (1). After 1970, the proportion of prestressed concrete bridges has been increasing steadily (1). As traffic flow increases and heavier truckloads are permitted, older bridges can become deficient. In addition, environmental

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attacks including freeze-thaw degradation and intrusion of chloride ions from deicing salts can cause active corrosion of reinforcing steel. Although current concrete mix designs and components are much more resistant to the forces of deterioration than older concrete, there are still problems with older bridges (2). Chase and Washer showed that there are more than 19,000 structurally deficient concrete bridges in the US in 1997 and the most serious types of deteriorated structural elements include decks, superstructure or substructure (1). Corrosion of reinforcement leading to concrete deck delaminations is a major maintenance repair/replacement cost for state DOT's and accurate mapping of top and bottom delaminations is needed for repair/replacement decisions. The Federal Highway Administration (FHWA) requires all bridges to be inspected at least every two years (2). The inspection of concrete bridge decks typically includes a delamination survey (with chain dragging for acoustic sounding that detects top rebar delaminations only), chloride sampling, phenolphthalein testing for carbonation depth, reinforcement concrete cover depth and core sampling. The drilled cores are also used to determine the "soundness", strength and thickness of existing deck concrete for ground truthing comparisons with NDE results.

This paper first summarizes a research project titled "Vehicle-Mounted Bridge Deck Scanner" funded by the NCHRP-IDEA program. Secondly, further advancements of the technology to evaluate delaminated (debonded) asphalt pavement layer conditions are briefly presented. The adaptation of the technology to asphalt by the authors was part of a Strategic Highway Research Program SHRP 2 R06(D) project conducted by the National Center for Asphalt Technology under the direction of Dr. Michael Heitzman of Auburn University. The NCHRP-IDEA research project focused on the development of technologies moving toward rapid inspection that can provide the following information about the bridge deck: (1) top and bottom delamination mapping; (2) internal conditions; including cracks, crack depth and concrete deterioration mapping; (3) thickness profiling and (4) stiffness/structural integrity of the deck.

BACKGROUND OF NDE METHODS APPLICABLE FOR BRIDGE DECKS

Sounding. Common chain configurations consist of four or five segments of 1 inch (2.54 cm). links of chain that are approximately 18 inches (45.72 cm). long (3). Distinctive hollow, drummy sounds are produced by chain dragging which are indicative of shallow delaminations. Other investigators have combined the chain drag apparatus to a microphone in an attempt to standardize and automate the evaluation (4). Although chain drags or hammer sounding are simple to use, most of the damage mapping is at the discretion of the operator due to different levels of experience and hearing among operators. In addition, delaminations located deeper than 3 to 4 inches (7.6 – 10.2 cm) are hard to detect by acoustic sounds generated due to flexural resonant vibrations of the delaminations.

Impact Echo (IE) Method. The IE method involves hitting the concrete surface with a small impactor (or impulse hammer) and identifying the reflected wave energy with a displacement (or accelerometer) receiver mounted on the surface near the impact point (5). Following the impact, the resulting displacement or acceleration response of the receiver is recorded. Although the resonant echoes are usually not apparent in the time domain, they are more easily identified in the frequency domain (linear displacement spectrum). Consequently, the time domain test data are processed with a Fast Fourier Transform (FFT) which allows identification of frequency peaks (echoes). If the thickness of a slab is known, the compression wave velocity (Vp) can be determined by the following equation:

$$Vp = 2*d*f/\beta \qquad (1)$$

where d = slab thickness, f = resonant frequency peak. The above equation is modified by a β (Beta) factor of ~ 0.96 for concrete slabs (5,6).

Spectral Analysis of Surface Waves (SASW) Method. The SASW method uses the dispersive characteristics of surface waves to determine the variation of the surface wave velocity (stiffness) of layered systems with depth (7).

Shear wave velocity profiles can be determined from the experimental dispersion curves (surface wave velocity versus wavelength) obtained from SASW measurements through a process called forward modeling (an iterative inversion process to match experimental and theoretical results. Materials that can be tested with the SASW method include concrete, asphalt, soil, rock, masonry, and wood. Applications of the SASW method include, but are not limited to: 1) determination of pavement system profiles including the surface layer, base and subgrade materials, 2) determination of seismic velocity profiles needed for dynamic loading analysis, 3) determination of abutment depths of bridge substructure, and 4) condition assessment of structural concrete. SASW can also measure crack depths (for cracks perpendicular to the surface) in bridge decks. The SASW method uses the dispersive characteristics of surface waves to evaluate concrete integrity with increasing wavelength (depth). Open, unfilled cracks will result in slower surface wave velocities. Weak, fire damaged and poor quality concrete (less stiff/lower elastic moduli) also produce slower surface wave velocities.

<u>Transducer Studies.</u> Several types of non-contact and rolling contact transducers were studied throughout the research. Non-contact transducers included in this study were microphones, laser vibrometers and microwave transducers. Note that non-contacting excitation of the concrete surface has been used in past studies (8) but is of less interest in this research project due to the relative ease of employing contacting solenoid impacts for excitation. Non-contact transducers are of significant interest because they may allow the evaluations to be performed more rapidly, which would allow greater speeds of a vehicle mounted bridge deck scanner. Of all non-contact transducers, microphones have been perhaps the most researched for IE and SASW testing (8, 9, 10, 11, 12 and 13). In general, non-contact IE testing using microphones has proven to be more difficult than non-contact surface wave testing because the separation of the impact source and microphone receiver is much less than in surface wave testing, which leads to interference from the direct air wave (10). The spacing between the receiver and impact source is critical in impact echo testing because the excitability of the S1 Lamb wave mode, which is the impact echo resonance in a slab structure (14), decreases drastically as the source-receiver spacing increases (15). An additional complication is the need for a longer time signal in the impact echo test to determine the resonance, whereas often times in surface wave testing only the first arrival (1st wave cycle) is considered, thus enabling sharp windowing functions to remove unwanted direct air wave arrivals. Zhu and Popovics demonstrated that sound insulation material can be used for shielding purposes to encapsulate (open on one end) the microphone receiver and reduce the direct air wave energy detected by it (10).

A preliminary experiment using microphones as non-contact transducers for the IE and SASW tests was performed on a 4-5 inch (10.2 – 12.7 cm) thick concrete slab. For the IE tests, both a microphone and a traditionally used contact accelerometer (grease coupled for mounting) were used side by side for comparison purposes. The microphone used in this study was an ADK SC-1 Small Capsule Condenser Microphone with an external 48V Phantom power supply. The studies included looking at the effects of the separation distance between the source and receiver so that the direct interference airborne wave can be excluded (after 15). An automatic solenoid impactor was applied at 1 inch (2.54 cm) intervals, starting at 4 inches away through 24 inches (60.96 cm) away from both transducers. When the microphone was close to the impact source, two wave modes (airborne and lamb waves) blended together in the IE waveform. When the source was further away from the microphone, the two wave modes could be separated to eliminate the airborne wave. However, the quality of the IE data from the microphone is not as good as those from the accelerometer.

For the SASW tests, two microphones of the same kind were used as non-contact transducers. The distance between the two microphones was 4 inches (10.1 cm) and a solenoid impactor was used as an impact source. The microphones were mounted 3 inches (7.6 cm) above the concrete slab and the source was located between 8 and 18 inches (20.3 and 45.7 cm) away from the closest microphone. Good quality SASW data (top trace in Figure 1) with a good coherence up to 10,000 Hz (2nd trace from top in Figure 1) was captured by both microphones. Note that the SASW data shown in Figure 1 were exponentially windowed after the large amplitude surface wave pulse traveled by them to eliminate other wave vibration modes. The surface wave velocity can be calculated from the phase plot (3rd trace from top in Figure 1) as a function of wavelength (velocity = frequency x wavelength (7)). The surface wave velocity is calculated to be approximately 7,000 ft/sec uniformly from wavelengths of 0.2 to 0.4 ft (6.1 to 12.1 cm) as seen in the last trace in Figure 1 which showed good agreement with the results from contacting displacement transducers.

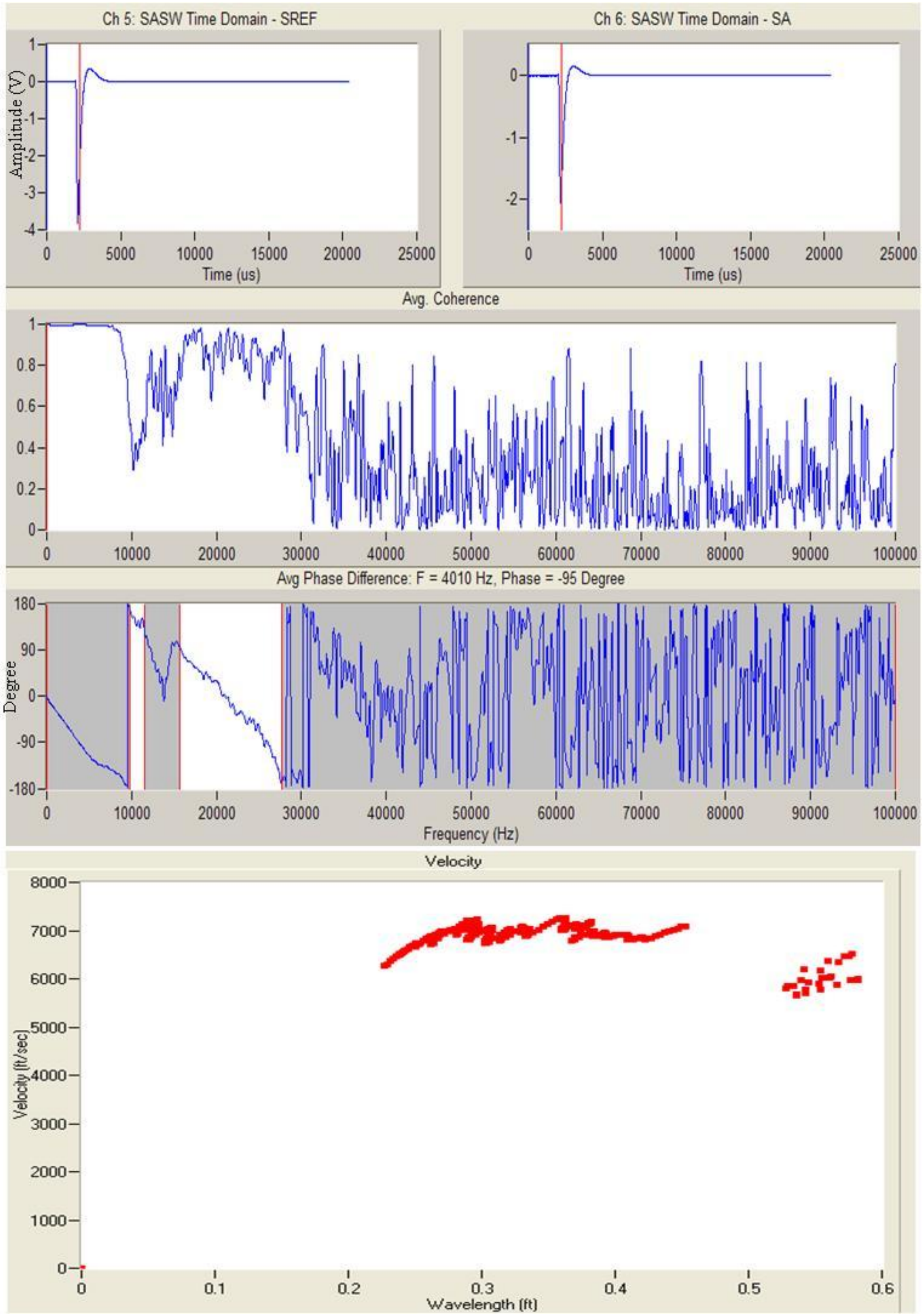

Figure 1 – SASW Data Processing from Non-contact Microphones

Non-contact Laser Vibrometers.. Laser vibrometers measure vibration using the Doppler shift effect and generally have a wide frequency range and excellent vibration resolution which are well suited to indoor laboratory testing. In addition the laser vibrometer has an ability to measure high vibration frequencies (up to 100 kHz depending on the unit) which make it suitable to measure surface waves in materials (16). A significant drawback of laser vibrometers is their cost, which typically ranges from $10,000 – $50,000 for a single receiver. Abraham et al. performed a successful study in which an extreme number of repetitive surface wave tests were performed on a variety of concrete samples using a laser vibrometer receiver mounted on a semiautonomous robot (17). The laser vibrometer has also been successfully implemented as a receiver for impact echo testing on concrete structures (18 and 19). In this preliminary experimental study, a laser vibrometer unit was rented from Polytec, Inc. The maximum Doppler frequency that the unit can acquire is 22 kHz. In this experiment, both a laser vibrometer and an accelerometer transducer were used as receivers. The laser vibrometer was attached to a tripod 40 inches (101.6 cm) above the tested concrete slab. A small Allen wrench was used as an impact source. In this case, a normal concrete velocity of 12,000 ft/sec was used to calculate the IE thickness. The left traces of Figure 2 show the IE data from the laser vibrometer on a 4.5 inch (11.4 cm) thick concrete slab and the right traces of Figure 2 show the IE data from the displacement transducer on an adjacent location. The top traces of Figure 2 are the time domain IE data and the bottom traces are the linear spectrum of the time domain data. Review of Figure 2 shows that the results from the laser vibrometer are as good in quality as the data from a displacement transducer.

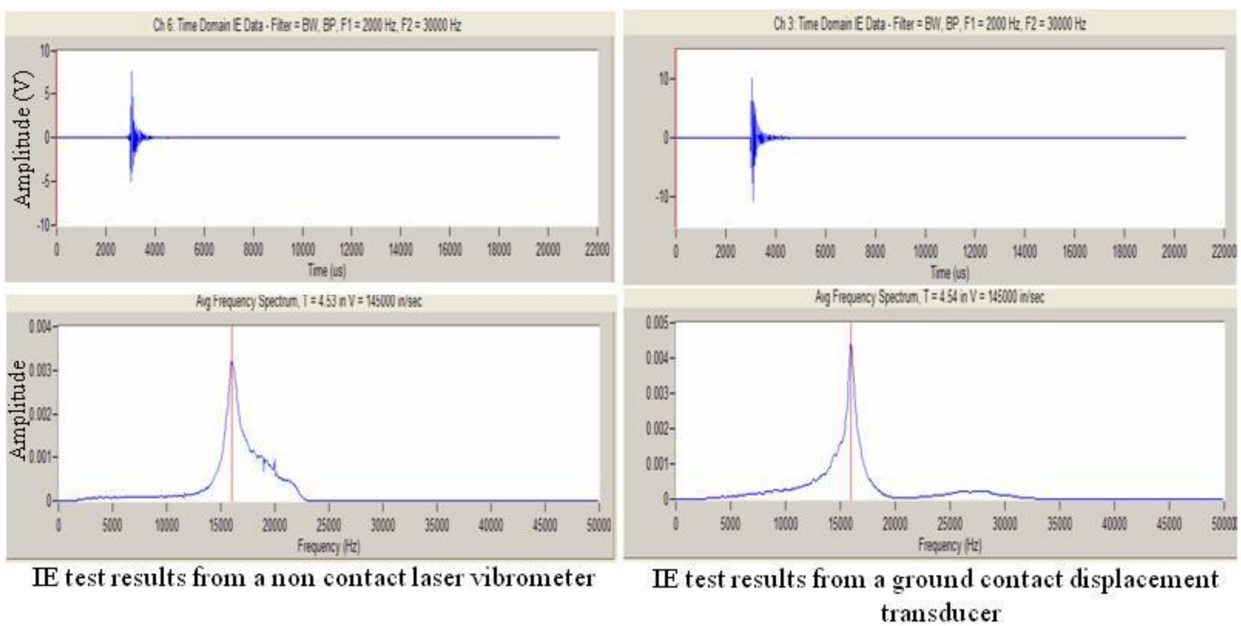

Figure 2 – Comparison of IE Data from a Non-contact Laser Vibrometer and Ground Contact Displacement Transducer on a 4.5 inch (11.4 cm) thick Concrete Slab-on-Ground

In an attempt to simulate a slow-moving scanning test, a test configuration was devised for movable IE tests which included the non-contact laser vibrometer mounted on a moving tripod (a tripod with wheels). In this setup, a laser vibrometer and the automated solenoid impactor from the handheld Impact Echo Scanner (see Figure 5) were used on a smooth 4 inch (10.1 cm) thick concrete slab. Figure 3 shows the laser vibrometer attached to a movable tripod (with 3 wheels) and the automated impactor (in the IE scanner) attached to the bottom frame of the tripod for the IE test. The IE scanner was attached to the frame of the tripod, therefore the IE scanner rolled at the same speed as the tripod moved. As it was rolled, the automatic solenoid impactor tapped the concrete slab approximately every inch along the scan line distance and the laser vibrometer constantly measured the Doppler shift that corresponded to vibration induced displacements in the slab. The unpublished IE results from the slowly and very smoothly moving laser vibrometer shows good quality IE data with a corresponding IE thickness of approximately 4.3 inches (10.9 cm). However, experiments with the laser vibrometer for IE scanning on rougher surfaces produced poor quality IE data which makes the use of the system very problematic for concrete decks which are typically much rougher than industrial slabs-on-ground..

The only rolling contact transducers used commercially in IE tests is the rolling displacement transducer for Impact Echo Scanning. The rolling Impact Echo Scanner (IES) was first conceived by the second author in the 1990's (20) and is based on the IE method (5 and 6). To expedite the IE testing process, an Impact Echo Scanning (IES) device has been developed with a rolling transducer assembly incorporating multiple sensors, attached underneath the test unit. When the test unit is rolled across the testing surface, an optocoupler on the central wheel keeps track of the distance. This unit is calibrated to impact and record data at intervals of nominally 1 inch (2.54 cm). If the concrete surface is smooth, a coupling agent between the rolling transducer and test specimen is not required. However, if the concrete surface is rough, water can be used as a liquid couplant. A comparison of the impact-echo scanner and the point by point impact-echo unit is shown in Figure 4. Typical scanning time for a line of 157 inch (4 m), approximately 150 points, is 60 s with a resolution of 1 inch (2.54 cm) along a scan line.

Figure 3 – Test Setup for Impact Echo Scanning

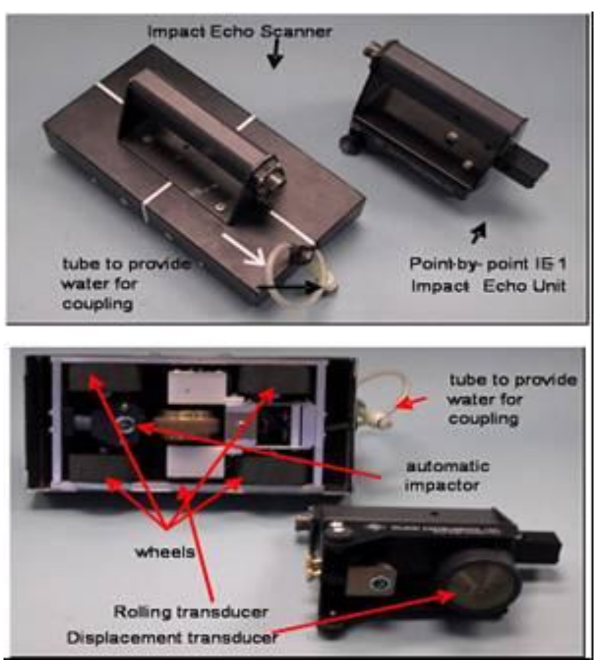

Figure 4 – Comparison between an Impact Echo Scanning Unit and Point by Point Impact Echo Unit

Transducer Selection for the Prototype Bridge Deck Scanner (BDS). The pros of the non-contact microphone are the inexpensive cost of the system and the ease of mounting. However, the cons include the poorer data quality when used to acquire IE data. The laser vibrometer provided excellent data quality when used to acquire IE data on a smooth concrete surface. However, the system is costly and becomes less economical when multiple laser vibrometers are required, and did not work well on rougher concrete surfaces. Considering the research team's prior experience in the rolling displacement transducer wheel and the cost of the displacement transducer, ground contacted displacement transducers were selected for the prototype BDS.

DEVELOPMENT OF A BRIDGE DECK SCANNER (BDS) PROTOTYPE

The design and development of the BDS prototype involved the fusion of knowledge gained from the literature review, discussions with other researchers, the extensive prior experience with the test methods and equipment, and preliminary investigations with non-contact transducers as well as significant mechanical and electrical research and development. In addition, since microphones are inexpensive, non-contact microphones were also incorporated as additional, non-contacting receivers in the BDS system.

The BDS wheel shown in Figure 5 was designed to include six piezoceramic displacement transducers with adjacent solenoid impactors at 6 inch interval spacings, resulting in a wheel circumference of 3 feet (91.4 cm) for a diameter of approximately 11.5 inches (29.2 cm). The six inch transducer/solenoid impact spacing was considered to provide relatively close measurement intervals consistent with a high data resolution bridge deck survey. The thin urethane wheel cover was added to protect the transducers, prevent dirt from entering the sensor housing and more importantly to increase sensor contact area and coupling. Six solenoids per wheel were used in the design. The solenoids were mounted to the side of the rolling transducer wheel in line with the sensor element, instead of suspending a single solenoid from the BDS frame, thus ensuring the solenoid height (distance between bridge surface and solenoid) remained constant to improve test consistency. A similar approach was taken with the electronics to power and acquire data from the sensors; instead of having a single very complex system housed independent of the rolling wheel, six small circuits were designed and incorporated into the wheel itself. This system has many advantages: first it reduces the number of "wires" which must be passed through the spinning hub assembly; second it makes the system more modular and robust where a single small component can easily be replaced if broken or damaged; and, third it makes the system more economical and simpler to produce six identical circuit boards than one large complex board.

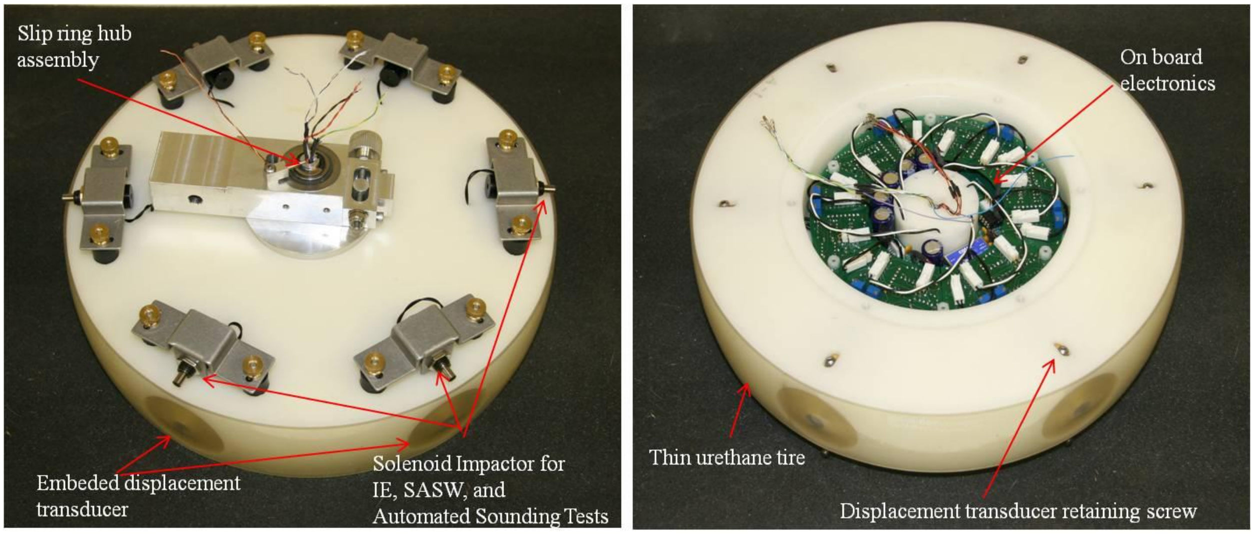

Figure 5 - Bridge Deck Scanner Transducer Wheel (left picture is of the hub assembly side/outside and the right picture is of the inside of the axle hub with dust cover removed)

With one transducer wheel, the BDS can perform only the IE test. To perform the SASW test, an identical transducer wheel oriented, synchronized and timed in a transverse (across the bridge lane) line was added to the BDS. As can be seen in Figure 6, the transducer wheels were mechanically connected using two u-joint slip couplers that would allow the wheels to move up and down independently and remain rotationally aligned such that one transducer from each wheel was in contact with the bridge deck surface at the same time. For SASW testing, the solenoid of the second wheel would be turned off so that only one solenoid was firing at a time. The second wheel would become far transducer wheel (far from the impactor) that measures the SASW data only. The wheels could also be offset 30 degrees apart in rotation and the solenoids on both wheels turned on to allow IE only testing on both wheels simultaneously (to perform two IE scan lines simultaneously) . A noncontact microphone was attached to a frame adjacent to an impactor. The purpose of the microphone is to perform an Automated Sounding test by “listening” to the shallow delamination.

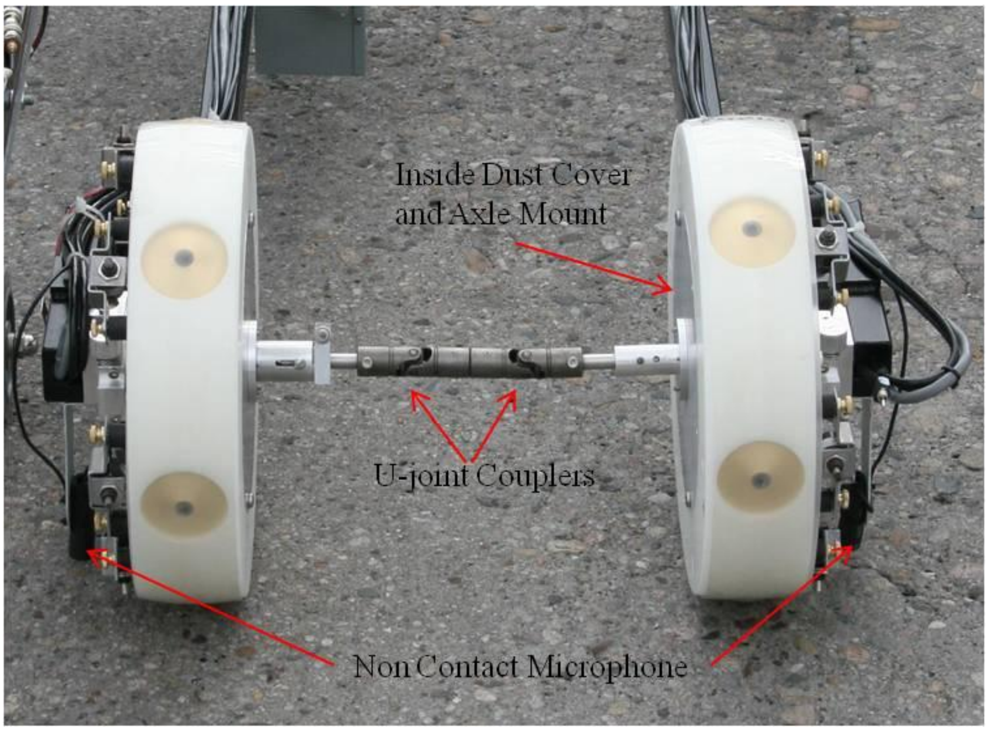

Figure 6 – Prototype Bridge Deck Scanner (BDS) with Two Transducer Wheels (offset for IE, aligned for SASW)

A steel beam was attached to the towing hitch of the vehicle in the transverse direction as shown in Figure 7. The beam had trailer ball hitches at 1 foot spacings and would allow test runs to be performed at any 1 ft (30.48 cm) interval location across a lane. An example BDS-IE scan line test result is presented in Figure 8 (from a new bridge). Similar data sets were combined to produce the BDS-IE results plots discussed later herein for the 1st Street Bridge which had delaminations. The BDS unit has also been towed by had across bridge decks using a cart.

Figure 7 – Prototype Vehicle Mounted Bridge Deck Scanner (BDS) on 1st Street Bridge in Casper

EXPERIMENTAL PROGRAM FOR BRIDGE DECK SCANNER (BDS)

The prototype BDS system was used on a 7 inch (11.78 cm) thick (design thickness) bare concrete deck of the 1st Street Bridge in Casper, Wyoming. Only the two east-bound lanes were evaluated during the field investigation. The bridge is curved and skewed at both ends, with a centerline distance of approximately 357 feet (108.7 m) and a deck width of approximately 36 ft (10.9 m) between curbs. Note that the concrete deck slab areas on top of girders are a couple inches thicker than the nominal thickness since the slab was thickened to bear on the steel girders.

<u>BDS Testing the Concrete Deck of the 1st Street Bridge.</u> The BDS prototype was used on the 1st Street Bridge to determine the deck damage conditions and locations. Note that other no-destructive evaluation methods including Ground Penetrating Radar (GPR) and Infrared Thermography (IR) were used on this bridge. However the test results from other techniques are not discussed herein. The BDS unit was hitched behind a truck and the data acquisition system (controller) was placed on the tailgate of the truck (Figure 7). A maximum speed of 1 to 1.5 mph (1.6 – 2.4 km/hour) was achieved for the testing in order to maintain good data quality. The BDS prototype performed Impact Echo tests using one transducer/impactor wheel in a line and SASW tests were conducted using both transducer/impactor wheels simultaneously. Testing was performed in test runs the full length of the bridge deck with a transverse spacing of 1 foot (30.48 cm). An example result for one IE scan line is shown in Figure 8. Thickness echo data shown on the left includes an approach slab from 0 to 20 ft (0 to 6.1 m) followed by 80 ft (24.38 m) of the bridge deck. The time domain signal in the upper right and its corresponding IE thickness echo frequency spectra in the lower right in Fig. 8. In some areas of the bridge significant gravel was present on the roadway and brooms were used to sweep the surface so it was free of debris.

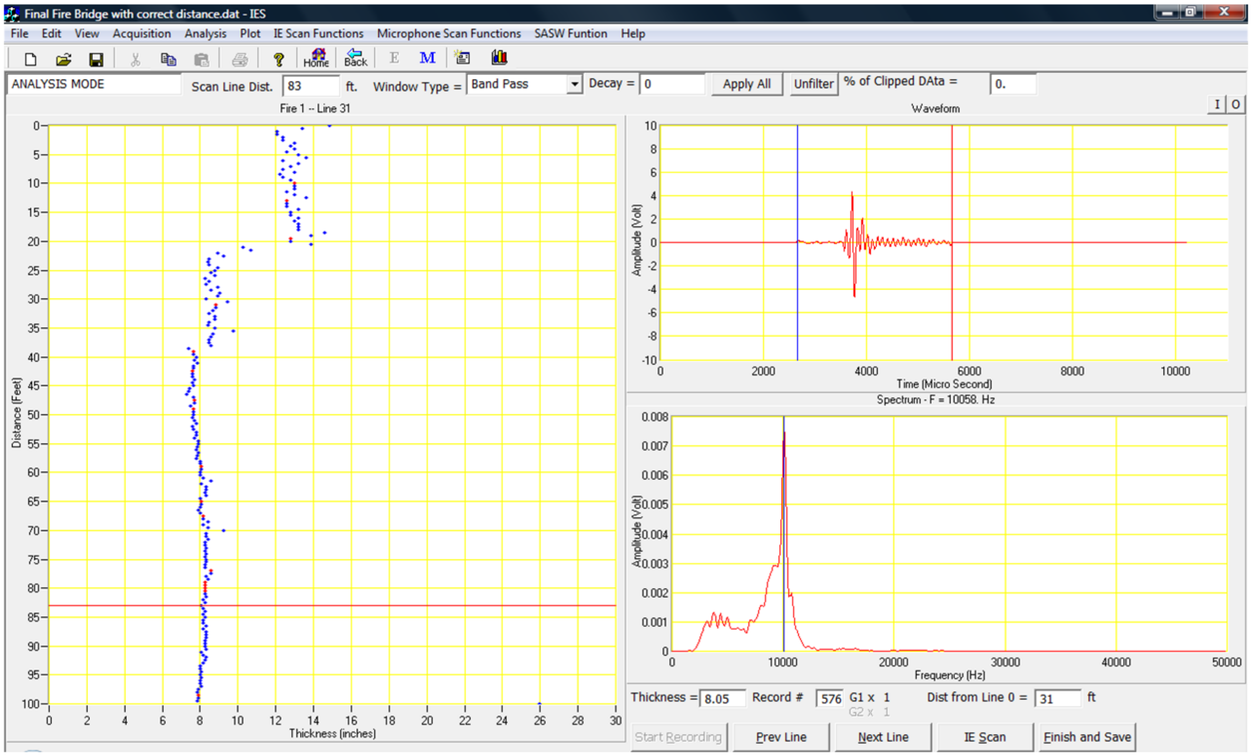

Figure 8 - Example Impact Echo Scanning Results from the BDS-IE system on a new bridge.

<u>Test Results from the 1st Street Bridge Deck Using the Prototype Bridge Deck Scanner.</u> Findings from the prototype BDS include test results from the IE component of the system in terms of delamination mapping. Test results from the SASW testing are not included herein since the bridge deck did not have significant cracking damage such as alkali-silica reaction, freeze-thaw or fire damage which would have reduced the structural stiffness/integrity (lower elastic moduli) of the concrete deck. The full range of graphical echo depth test results from the IE component of the BDS is presented in Figure 9. The plot is a surface thickness tomogram presented in a 3D thickness tomogram to elaborate all conditions including top and bottom delamination of the tested concrete deck. The color thickness/echo depth scales range from 4 to 17 inches (10.1 – 43.2 cm). The majority of the indicated anomalies are predominantly top delaminations based on the test results (indicated by apparent "thick" echoes of 13 inches and greater due to the delamination flexural response). The green color represents areas where the thickness results ranged from 7.5 to 9 inches (20 – 22.8 cm) indicative "sound concrete" which correspond to echoes indicative of normal thickness deck areas. Note that although the design thickness of the deck was 7 inches, drilling from 15 locations on the deck showed that the actual thickness of these areas ranged between 7.5 – 9 inches. Dark green and light blue represent areas with greater thickness echo results of approximately 9-10 inches (22.8 – 25.4 cm) which were typical from areas with thickened slabs over the steel girders underneath the deck (note linear features in Figure 8 of these colors). Purple, Gray, and black colors represent areas with top delaminations that are associated with the lower frequency flexural response from BDS-IE scanning that correspond to "thick" apparent echo depths and reflect the hollow, drummy sound of shallow delaminations identified in acoustic chain dragging sounding). Yellow and red colors represent areas with thinner thickness results or more likely areas with either bottom delamination or internal cracks.

The full depth BDS IE scanning results are presented in Figure 10. A shallow delamination map of the bridge deck by the BDS IE system and the delamination map from chain drag sounding by the Wyoming DOT are presented in Figure 10 for comparison. The quantity of probable delaminations detected from the BDS was estimated to be 1,004 sq ft (93.27 sq meter) or 11.1 percent of the tested deck surface area which compares well with the results from the acoustic chain drag sounding. In addition, review of Figures 9-10 reveal a more precise delineation of deck integrity/delamination/thickness conditions to within 0.5 sq ft (0.046 sq meter) of deck damage conditions with both top and bottom delamination and other deck integrity information from the IE component of the BDS. The IE echoes shown in blue which appear as 5 horizontal lines in Figure 9, are due to increased thickness echo depths from the thickened slab over girder areas. This further validates the accuracy of the Impact Echo scanning data obtained by the BDS prototype.

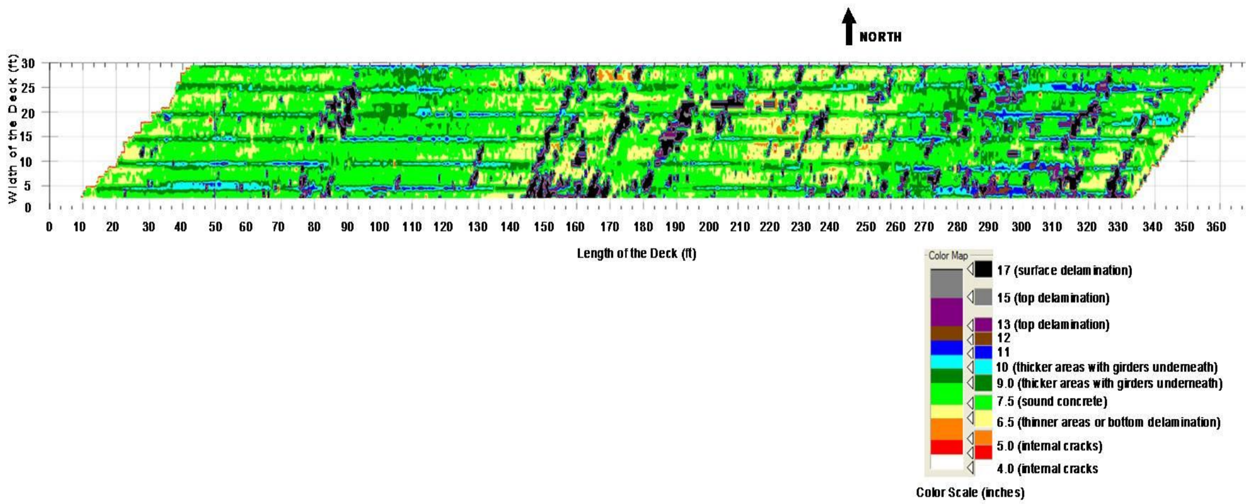

Figure 9 – Test Results from the Bridge Deck Scanner – Impact Echo (IE) Full Range Depth Echo Components

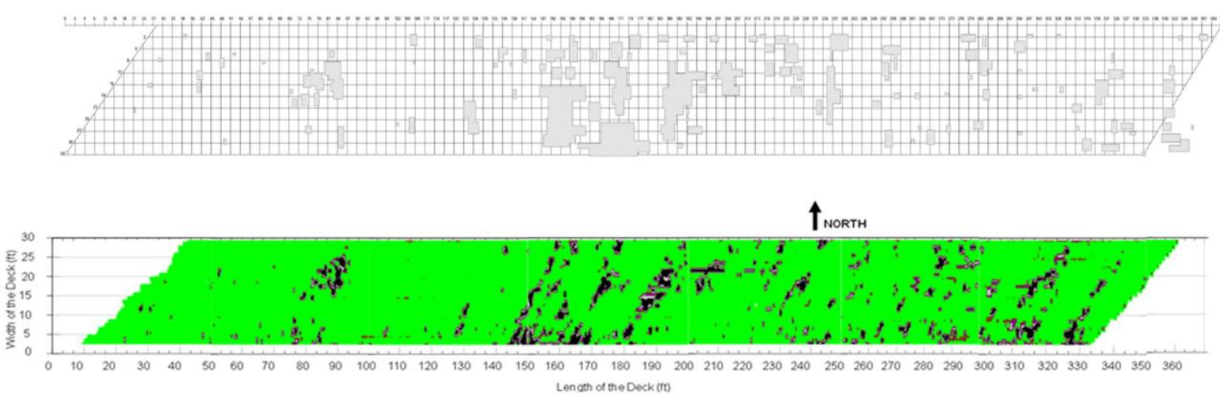

Figure 10 – Impact Echo Test Results from the BDS Prototype from the 1st Street Bridge Deck Showing Top Delamination Mapping Compared with the results from Acoustic Sounding by Chain Dragging (top delaminations shaded) **-** Probable Top Delamination Area from BDS-IE tests = 1,004 sq ft (11.1%)

PRELIMINARY BDS RESULTS FOR NDE OF ASPHALT PAVEMENT DELAMINATIONS

The Bridge Deck Scanner (BDS) was evaluated as part of the Strategic Highway Research Program 2 (SHRP 2) R06(D) research grant entitled "Nondestructive Testing to Identify Delaminations between HMA Layers" which is being conducted by Dr. Michael Heitzman of the National Center for Asphalt Technology, Auburn University. The project background and objectives of the SHRP 2 R06(D) project are as follows:

"Project Background **-** One of the more serious problems that can occur in hot-mix asphalt (HMA) pavements is delaminations between HMA layers. Several instances have been documented where pavements with delamination problems have experienced significant early damage. The presence of undetected delaminations and/or discontinuities in asphalt pavements also provides paths for moisture damage and development of other distresses including stripping, slippage cracks, pavement deformation, and reduction in pavement strength. Delaminations are also key contributors to top-down cracking of HMA pavements. A rapid nondestructive test method is needed to determine the existence, extent, and depth of delaminations and/or discontinuities in asphalt pavements so that the appropriate rehabilitation strategy can be determined.

Objectives **-** The main objective of this study is to identify and develop nondestructive testing (NDT) techniques that are capable of identifying and determining the extent and depth of delaminations and discontinuities in HMA pavements. To achieve this objective the researchers shall determine key indicators that may be used to identify potential areas of delamination including lack of bond, stripping, and other causes. The NDT techniques developed under this project should provide rapid results with near 100% continuous coverage of the pavement area."

<u>Application of Bridge Deck Scanner to Asphalt Pavement Delaminations.</u> The initial research involved evaluation of both laboratory and full-scale pavement sections with constructed delaminations at the NCAT laboratory and test track at Auburn, Alabama. Based on this research, Impact Echo and Spectral Analysis of Surface Waves scanning with the BDS showed sufficient promise that the technology was selected for further evaluation in the second field phase of the project and the BDS was expanded from 1 pair of wheels to 3 pairs of wheels. The BDS was subsequently evaluated with the 3 wheel pairs at the NCAT test track and asphalt highway pavements in Florida and Kansas (shown on the Kansas pavement below in Figure 11). The wheels were spaced at 0.5 ft (0.15 m) apart for combined IE/SASW testing and shifted across the rear of the truck to test a whole lane in 2 passes.

Figure 11 – Bridge Deck Scanner on Kansas Asphalt Pavement site with 3 pairs of wheels spaced 0.5 ft (0.15 mm) apart for combined Impact Echo and Spectral Analysis of Surface Waves scanning.

Preliminary Results of Bridge Deck Scanner for Asphalt Pavement Delaminations. The SASW results were found to best indicate delaminations between asphalt pavement layers at the NCAT site. Impact Echo tests also showed some promise for indicating asphalt delamination, but due to the temperature dependent, viscous behavior of ahalt it was difficult to measure resonant echoes indicative of asphalt delamination (debonding). Delaminations consisted of thin paper and baghouse dust and other simulated defects at the NCAT test track. Example dispersion curves of velocity vs. wavelength from SASW phase plots (see Figure 1) are presented in Figures 12 and 13 below for baghouse dust and thin paper delaminations, respectively. Review of these figures indicates a decrease in the surface wave velocity at the delamination depth. This proved to be a reliable indicator of the presence of most of the constructed delaminations at the NCAT test track.

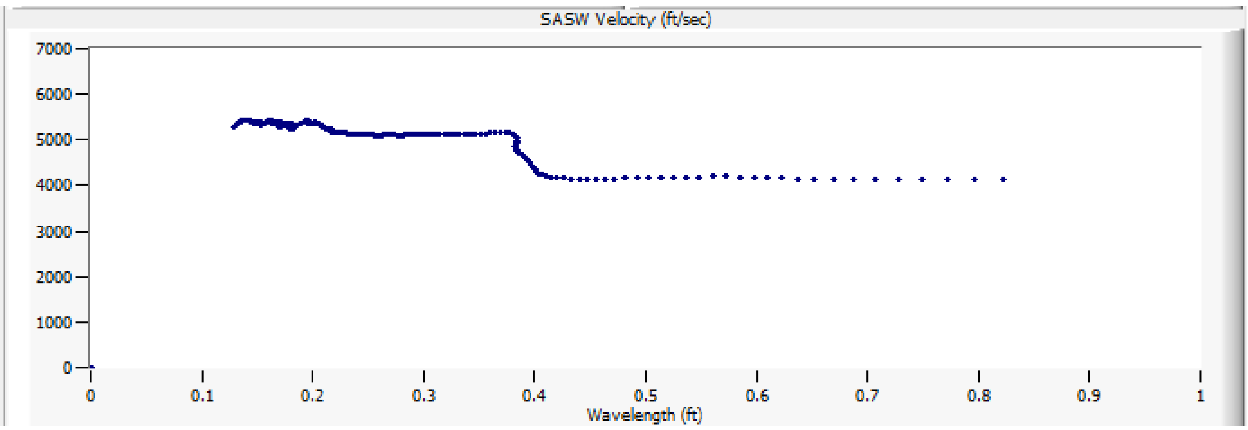

Figure 12 – SASW Dispersion Curve Example of Baghouse Dust Delamination built at 5 inches deep – note surface wave velocity decrease from ~5200 ft/s (vertical scale) to ~4300 ft/s at a wavelength of 0.4 ft (~ 5 inches) that indicates the presence of the delamination

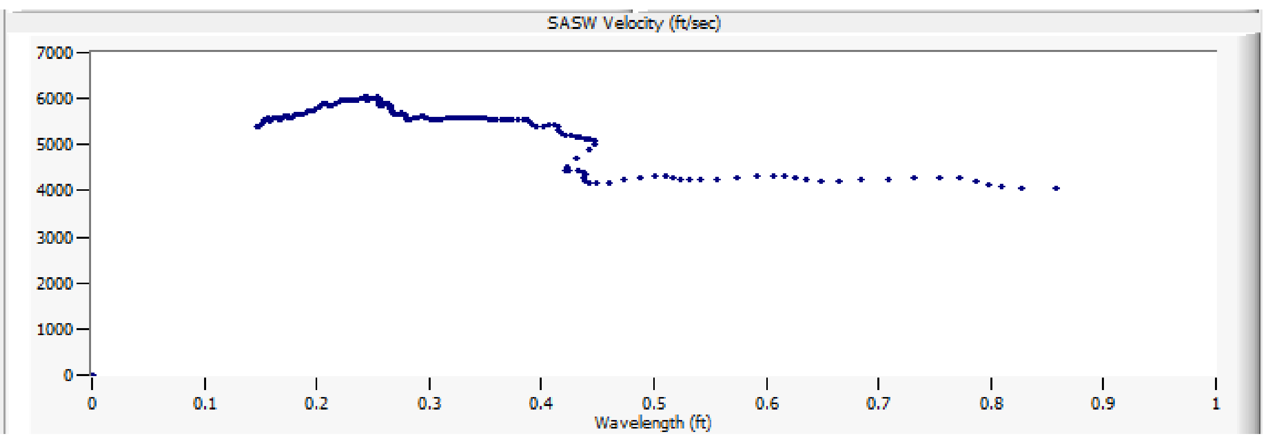

Figure 13 – SASW Dispersion Curve Example of Thin Paper Delamination built at 5 inches deep – note surface wave velocity decrease from ~5300 ft/s (vertical scale) to ~4300 ft/s at a wavelength of 0.43 ft (~ 5 inches) that indicates the presence of the delamination

In order to plot the depths of delaminations in a 2-D plan view fashion, gray scale plots were produced at depths of every 0.1 ft to show sound asphalt with no delamination as black and slower velocity asphalt due to delamination grading from gray to white. Section 1 (0 - 25ft) was built with no bond between the 5 inch HMA overlay and underlying PCC pavement. Delamination is indicated by slower velocity gray to white regions in Figure 14 – note that some areas exhibit good bonding per the SASW results. Baghouse dust was used in the 25 ft long Section 1 to simulate debonding from a width distance of 4 – 6 ft and thin brown paper was used from a distance of 6 – 10 ft.

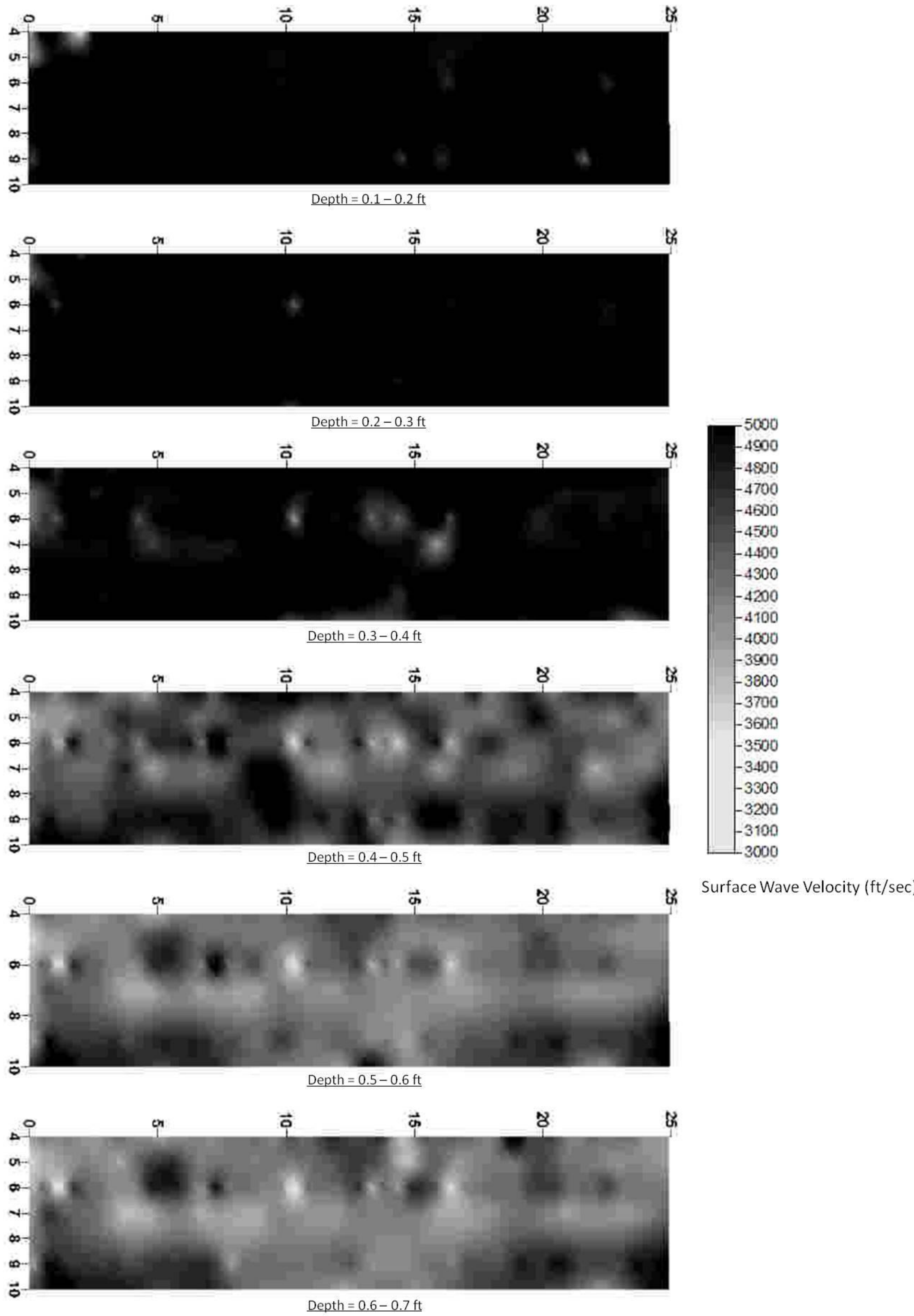

Figure 14 – Plots of Asphalt Pavement Delamination vs. Depth for 5 inch (0.42 ft) dust (4-6 ft) and thin paper (6-10 ft) delamination - the white-gray delamination areas are clear for most of this section at 0.4-0.5 ft and deeper.

SUMMARY

The BDS NCHRP IDEA research project fulfilled its proposed objectives by developing a product (the prototype Bridge Deck Scanner) that can determine the internal conditions of concrete bridge decks in a quick scanning fashion with a high degree of accuracy on an automated basis. This BDS can employ three non-destructive evaluation methods simultaneously depending on the nature of defects encountered in the bridge deck. These methods include the Impact Echo and Spectral Analysis of Surface methods (IE and SASW). The Impact Echo test results from the BDS (from the First Street Bridge Deck in Casper, Wyoming) indicated both top and bottom concrete delaminations with a resolution of 0.5 sq ft (0.046 sq meter) while chain dragging can only locate top delaminations and is less accurate. Although the current speed of the scanning is approximately 1 – 1.5 mph (1.6 – 2.4 km/hour), several tests can be performed simultaneously to accelerate the testing process.

Preliminary results of the SHRP 2 R06(D) project indicate that the SASW method was successful in identifying most delaminations at the Auburn University NCAT test site by measuring a decrease in surface wave velocity that was typically on the order of 10 to 20%. This velocity reduction was found to occur at wavelengths that corresponded to the constructed delamination depths. The BDS scanner is currently being evaluated on two actual asphalt pavement sites in Florida and Kansas and the research is anticipated to be completed in the near future.

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