Spectral Analysis of Surface Waves Scanning to Identify Debonding Conditions between HMA Layers in Pavements

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ABSTRACT

This paper presents a recently developed system used for condition assessment of hot mix asphalt (HMA) pavements to detect debonding between layers of HMA pavements. The study was partly funded by the Strategic Highway Research Program 2 (SHRP 2) - R06D research project titled "Nondestructive Testing to Identify Delaminations between HMA Layers" through the National Center for Asphalt Technologies (NCAT). The objective of the study was to develop a reliable technique to determine internal condition of HMA pavements including debonding conditions between each layer. An Impact Echo and Spectral Analysis of Surface Waves Scanner (IE/SASW Scanner) prototype (originally developed for condition assessment of bridge decks) with up to three pairs of transducer wheels using Spectral Analysis of Surface Waves scanning was employed in this project. This paper includes background of the development of the IE/SASW Scanner and a case study performed on HMA pavements of known conditions at the NCAT Pavement Test Track. The research investigation was performed as a "blind" study, with the actual known pavement conditions revealed to the research team after initial data analysis and reporting of detected delamination conditions was completed.

INTRODUCTION

The bonding condition between layers of HMA pavements is an important issue regarding long term performance for multi-layered pavement structures. Good bonding conditions between layers will lead to a longer service life of multi-layer HMA pavements (1 and 2). Development of reliable, non-destructive evaluation techniques that can accurately identify locations and depths of debonding are critical. Identification of these defects allows agencies to repair the discontinuity before affecting the long term safety and service life of the pavement. This paper includes the background of the IE/SASW Scanning system development and a blind case study investigation on HMA pavements of known conditions.

BRIEF BACKGROUND OF THE SPECTRAL ANALYSIS OF SURFACE WAVES TECHNIQUE

The Spectral Analysis of Surface Waves (SASW) method is typically applied to structural elements to estimate surface-opening crack depths, fire damage and freeze-thaw damage depths, and the measure relative concrete quality. It can also be used for thickness profiling of pavements, including asphalt and layer systems. The method uses the dispersive characteristics of surface waves to determine the variation of the shear wave velocity (stiffness) of layered systems with depth. Aouad et al. described the theory of the SASW test in details (6). Surface opening cracks, honeycomb zones, fire damage, and other flaws with create an effective "layer" of low velocity material with a depth which can be measured. In general once the shear wave velocity profiles are determined, shear and Young's moduli of the materials can also be estimated through the use of simple mathematical equations. The shear wave velocity profiles (shear wave velocity versus depth) are determined from the experimental dispersion curves (surface wave velocity versus wavelength) obtained from SASW measurements through a process called forward modeling or through an inversion process. The shear wave velocity measurements can be used to compare concrete areas to locate zones of weak or degraded concrete. In this project, the shear wave velocities were not calculated and only the surface wave velocities at different depths were used as an indication for pavement debondings. The SASW method can be performed on any material provided there is an accessible surface for receiver attachments and source impacting.

IMPACT ECHO/SPECTRAL ANALYSIS OF SURFACE WAVES SCANNER (IE/SASW SCANNER)

The IE/SASW Scanner was recently developed by the research team at Olson Engineering as part of research funded by the National Cooperative Highways Research Program – Innovations Deserving Exploratory Analysis program (3). The system was originally developed for rapid condition assessment of bridge decks using a pair of transducer wheels, and thus the name "Bridge Deck Scanner (BDS)". As part of the research project funded by the SHRP 2 (R06D) research program through NCAT, the system was later expanded to up to three sets of identical transducer wheels to allow for more rapid testing. The name of the system was changed to Impact Echo/Spectral Analysis of Surface Waves Scanner (IE/SASW Scanner) to make it more generalized to both bridge and pavement applications. Figure 1 shows a transducer wheel assembly. The transducer wheel was designed to include six piezo-ceramic displacement transducers at 6 inch (152.4 mm) spacings, resulting in a wheel circumference of 3 feet (0.91 meter) or a diameter of approximately 11.5 inches (279.4 mm). The 6 inch (152.4 mm) transducer spacing was utilized to provide relatively close measurement intervals consistent with a high data resolution bridge deck survey. The six transducers incorporated into each wheel are spring mounted with rubber isolators and captured with a thin replaceable urethane tire approximately 2.5 inches (63.5 mm) wide. The thin urethane tire was added as a dust cover to prevent dirt from entering the sensor housing and, more importantly, to increase sensor contact area and improve sensor coupling. The transducer wheel design of the IE/SASW Scanner uses a solenoid impactor to impart energy into the material surface, creating high amplitude signals which are easily measured by the transducer. The solenoids were mounted to the side of the rolling transducer wheel in line with the sensor element, thus ensuring the solenoid height (distance between material surface and solenoid) remained constant to improve test consistency. The urethane tire, large impacting solenoids, and overall sensor weight (approximately 25 lbs or 11.3 kilogram), which affects contact pressure, are the primary improvements over the rough surface performance of the BDS system.

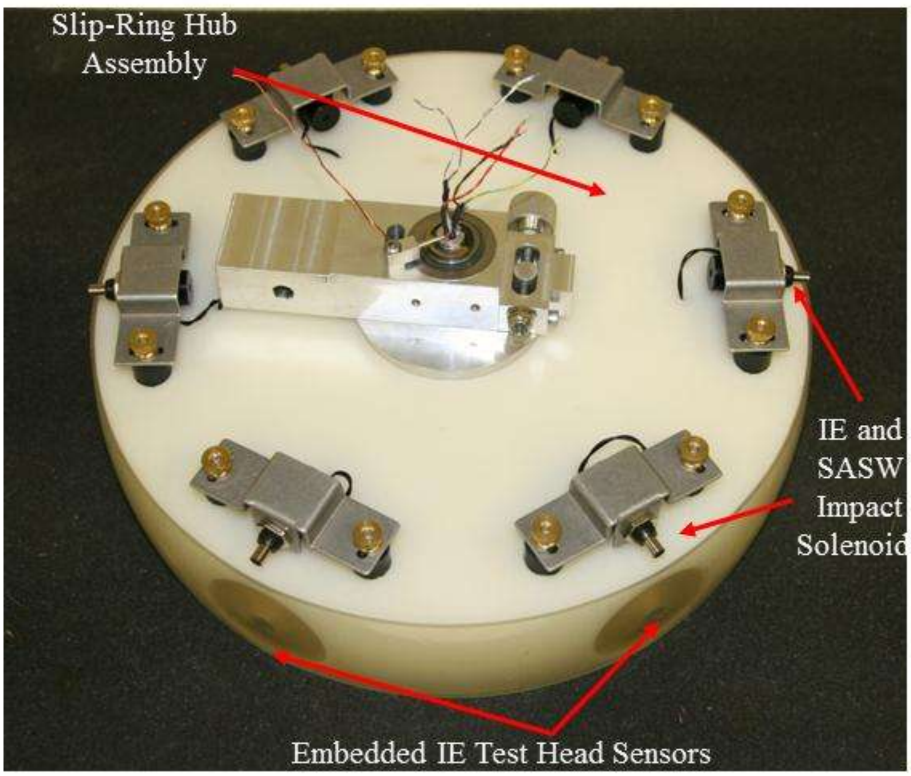

Figure 1 – Transducer Wheel Assembly

Two identical transducer wheels constitute a "set", which work in concert with one another during testing. The IE/SASW Scanner can be equipped with up to three sets of transducer wheels. The system can be easily attached to either a vehicle hitch as shown in Figure 2 with three sets of transducers, or a scanning cart when only one set of transducer wheels are used.

The IE/SASW Scanner can perform:

1) Impact Echo tests on each transducer wheel simultaneously with the transducer and impactor on adjacent wheels offset to avoid signal interference. This set-up is ideal for condition assessment of bare concrete decks if top delamination and general integrity are the primary concern. The spacing between the two adjacent transducer wheels can be set between 6 inches (0.15 meter) and 2 feet (0.61 meter) depending on the desired scan resolution.

2) Impact Echo and Spectral Analysis of Surface Waves can be scanned simultaneously by aligning the transducer elements of both transducer wheels within a "set". The first transducer wheel (with the impactors activated) collects IE data as well as the first channel of SASW data. The second wheel (with the impactors off) collects the second channel of SASW data. Both IE and SASW tests can be performed simultaneously in a single scan. This setup provides additional information for assessment of complex pavement structures such as layered HMA or concrete decks with asphalt overlays, which, in past experience, have been problematic for IE testing alone.

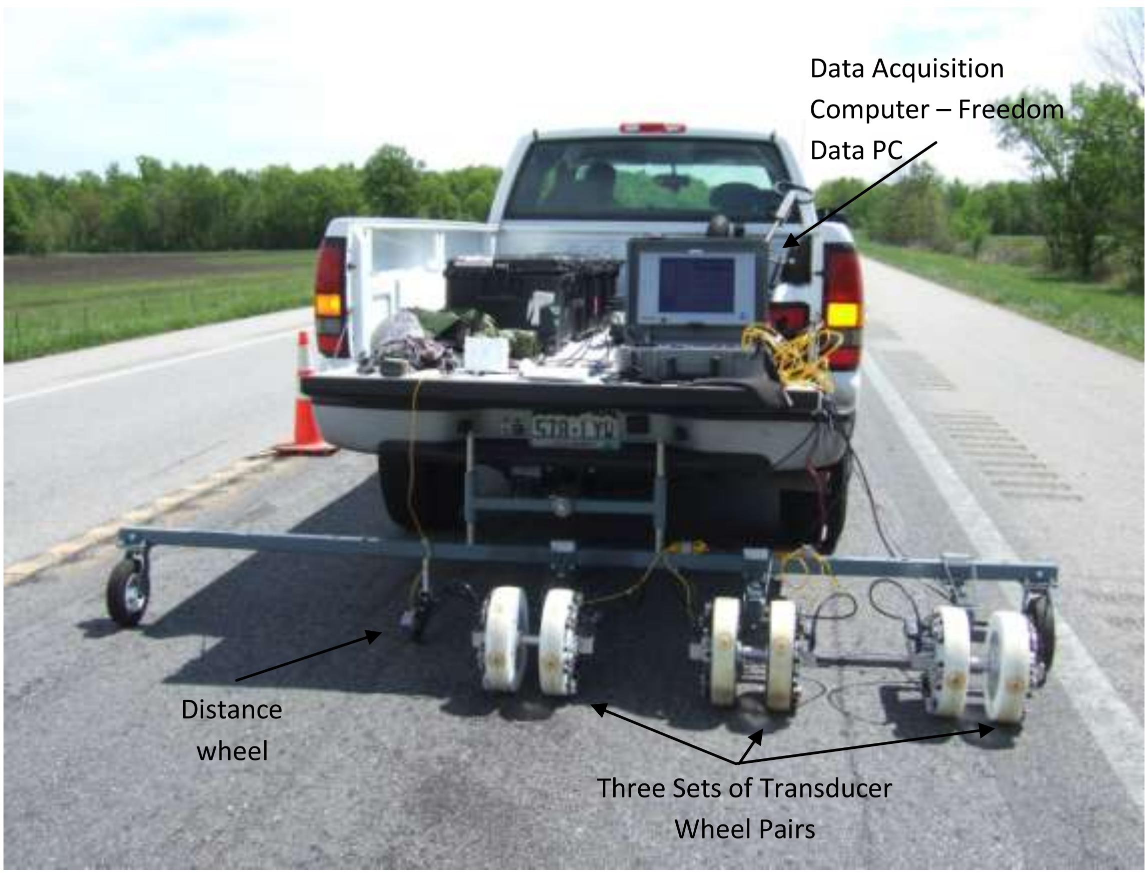

Figure 2: Current IE/SASW Scanning System, showing the SASW test set-up of 6 inch (152.4 mm) transducer spacings with a distance of 2 feet (0.61 meter) between pairs on HMA Pavement.

CASE STUDY: IE/SASW SCANNING ON A HMA PAVEMENT AT NCAT SITE

Project Background

The main objective of the SHRP 2 Project R06(D) is to identify and develop rapid nondestructive testing (NDT) techniques with 100 percent continuous coverage that are capable of identifying and determining the extent and depth of delaminations and discontinuities in HMA pavements. The IE/SASW Scanner developed by Olson Engineering was one of the technologies that NCAT evaluated. During early stages of the research the hardware and software of the IE/SASW Scanning system was expanded to allow connection of up to three sets of transducer wheels to widen the testing field for actual real world pavement testing scenarios. The system was then evaluated in a "blind" research study to measure the known HMA pavement conditions at the NCAT Pavement Test Track. The known pavement conditions were not revealed to the researchers until after data analysis and reporting of results was completed.

Construction of Pavement Test Sections at the NCAT Pavement Test Track

NCAT constructed ten test sections at the NCAT test track facility located near Auburn, AL. Pavement conditions ranging from complete debonding to good bonding were simulated at the interfaces between dense-graded asphalt layers. Good bonding conditions were ensured by using a tack coat, while poor bonding conditions were constructed by using bond breakers such as baghouse fines and multiple layers of heavy craft paper between asphalt lifts. In addition, a 25.4 mm (1 inch) thick un-compacted coarse fractionated RAP material was used to simulate a "stripping" condition. Each test section is 25 feet (7.62 meter) in length and 12 feet (3.66 meter) in width.

IE/SASW Scanning for Multi-Layers HMA Pavements to Detect Bonding Conditions

An IE/SASW Scanner using the SASW measurement equipment setup was used to assess the condition of the test sections. For this setup, the solenoid impactors were activated for one transducer wheel and off for the second transducer wheel. This setup allows the Impact Echo Scanning and Spectral Analysis of Surface Wave Scanning to be performed simultaneously in a single scan. The SASW data gave clear indications of bonding conditions and the IE data were also used in the analysis as a comparison. The background and theory of the SASW test method can be found in many publications (5 and 6).

SASW Data Interpretation

Sound pavements typically yield a high and relatively constant surface wave velocity observed as a flat, horizontal line in the dispersion curve throughout the depth of the pavement. A typical example of a "Sound" pavement condition is shown in Figure 3. The presence of a sharp drop in the dispersion curve (surface wave velocity vs wavelength or depth) was found to be a reliable indication of debonding between layers of HMA pavements. The depth or wavelength of the velocity drop directly relates to the depth of the debonding. Figure 4 presents a dispersion curve from a location from Section 1 from the NCAT test track. The actual as-built plan at this test location showed baghouse dust at a depth of 5 inches (127 mm) to simulate a debonding conditions between the HMA lift and underlying concrete. Review of Figure 4 shows a sharp drop in the surface wave velocity at a depth of 5 inches (125 mm), which agreed with poor bonding at the depth of the HMA layer boundary with simulated debonding. Figure 5 presents a dispersive curve from a location from Section 6 from the NCAT test track. The actual as-built plan at this test location showed stripping between depths of 2 inches (50.8 mm) HMA surface lift and 3 inches (76.2 mm) HMA leveling lift. Review of Figure 5 shows a sharp drop in the surface wave velocity at a depth of 3 inches (76.2 mm), which agreed with the approximate stripping depths at that location.

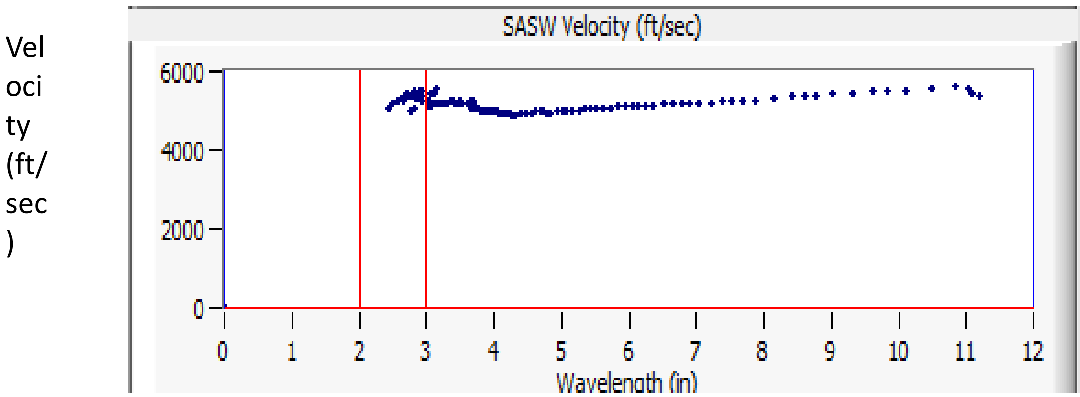

Figure 3 – A Dispersion Curve from a Sound Location on NCAT Pavement

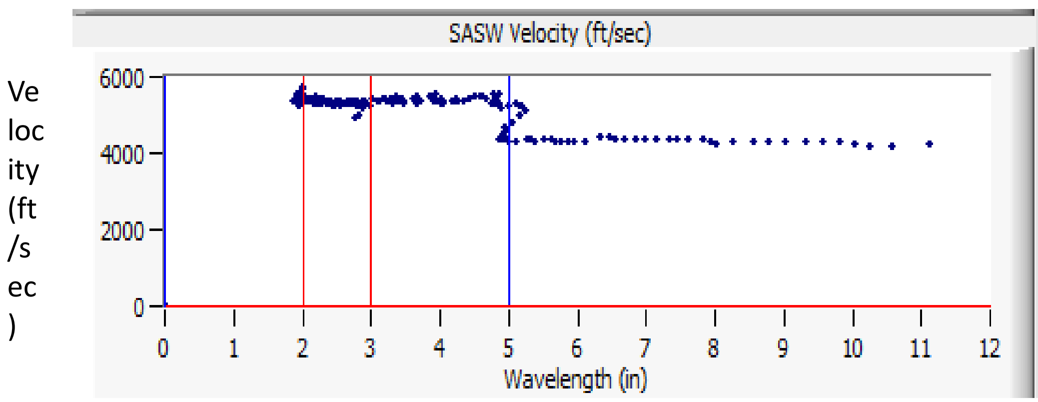

Figure 4 – A Dispersion Curve from a Location from Section 1 with Debonding at a Depth of 5 inches (127 mm)– Note Drop in Velocity at Approximately the Same Wavelength (Depth)

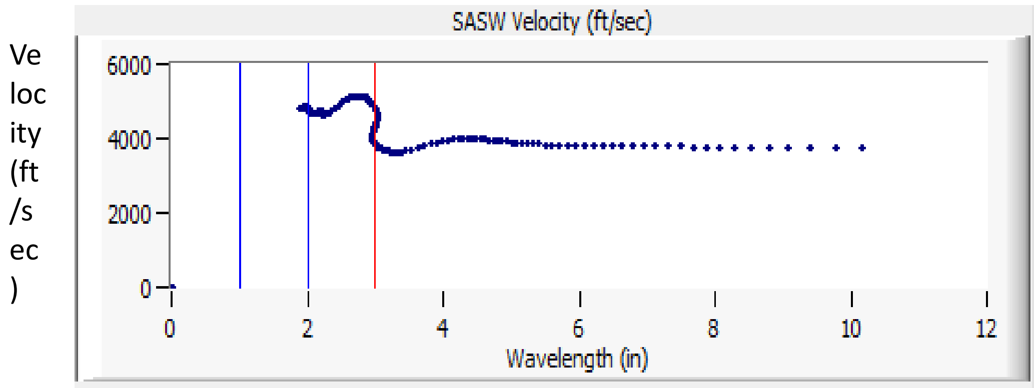

Figure 5 – A Dispersion Curve from a Location from Section 6 where Simulated Stripping between Depths of 2 inches (50.8 mm) HMA surface lift and 3 inches (76.2 mm) HMA leveling lift Note Drop in Velocity at Approximately the Same Wavelength (Depth)

Test Results from the IE/SASW Scanner – SASW Scanning Component

The test results are presented as plan view images of the test area with the grayscale representing the average surface wave velocity at a particular depth range. Multiple plots are presented to cover depths from 0.1 to 0.8 feet (30 to 244 mm) from the surface. Surface wave velocities are presented in a grayscale ranging from 3,000 ft/sec (914 m/s) - shown in light gray color to 5,000 ft/sec (1,524 m/s) - shown in black color. The higher the surface wave velocity, the better the condition of the asphalt pavement. Anomalies are revealed as light colored spots or areas, where the velocities are lower than normal conditions. Creating multiple plots by representing slices of data at different depth ranges allows the depth of anomalies to be determined. Figures 6 to 8 present the surface wave velocity profiles from three out of ten sections of the NCAT Pavement Test Track. Note that the test results from all ten sections represented the actual conditions of the test track relatively well. However, only the test results from the clearest three sections are presented herein.

Reviews of Figure 6 (Section 1) show a significant drop of surface wave velocities indicating likely debonding between depths of 4.8 and 6 inches or 0.4 and 0.5 ft (121.9 and 152.4 mm). Reviews of Figure 7 (Section 6) show low velocities from measurement Grid Lines 9 and 10 at the shallow depth of 1.2 – 2.4 inches or 0.1 – 0.2 ft (30.5 – 60.96 mm). This is indicative of debonding at depths between 1.2 and 2.4 inches or 0.1 and 0.2 ft (30.5 – 60.96 mm). Last, reviews of Figure 8 (Section 7) show that the surface wave velocities are relatively constant throughout the depths indicative of sound pavements except at the lower left corner (a few test locations) where the test results show a shallow delamination between 1.2 and 2.4 inches or 0.1 and 0.2 ft (30.5 – 60.96 mm).

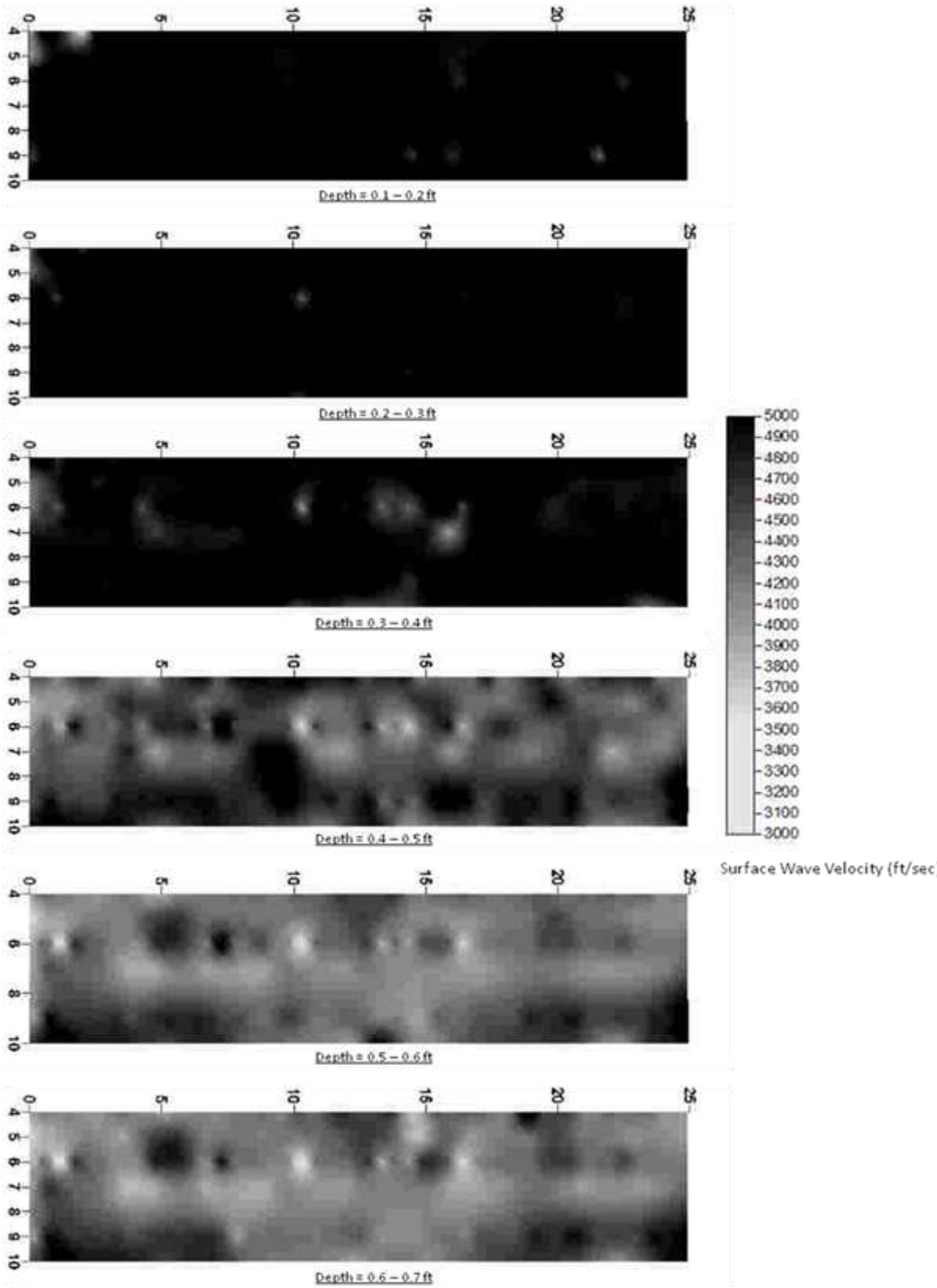

Figure 6 – Profile (Depth) Plot of Surface Wave Velocities from Section 1

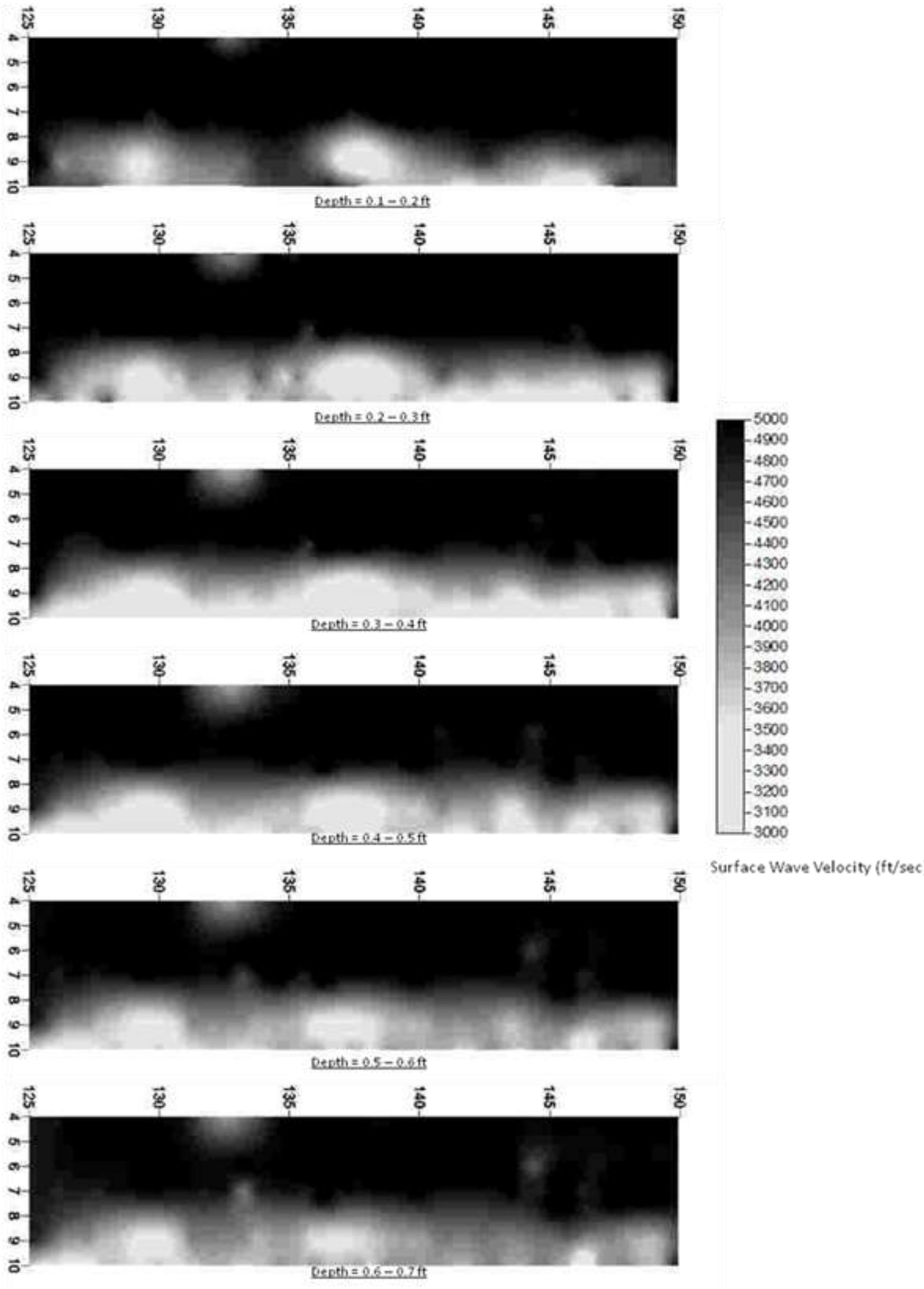

Figure 7 – Profile (Depth) Plot of Surface Wave Velocities from Section 6

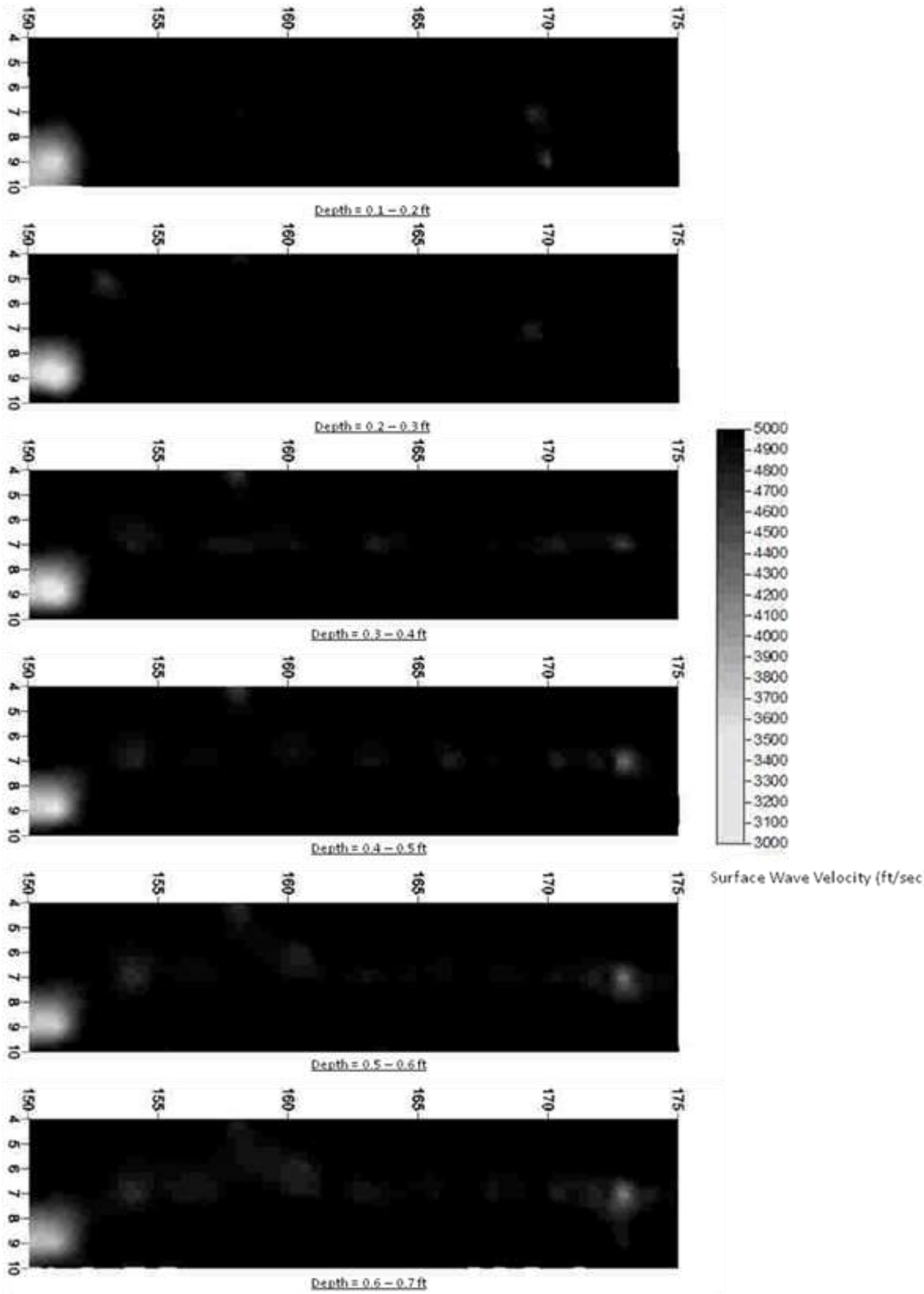

Figure 8 – Profile (Depth) Plot of Surface Wave Velocities from Section 7

Discussion of Test Results and Comparisons between the SASW Test Results and Actual Conditions

The known as-built conditions of Sections 1, 6 and 7 are summarized below:

- Section 1 – There is no bond between 5 inches or 0.42 feet (127 mm) of HMA overlay and the concrete pavement throughout the whole section. Baghouse dust was used as the bond breaker for half of the width of the section and paper was used on the other half.
- Section 6 - Simulated stripping in the wheel path between 1.92 inches or 0.16 feet (50.8 mm) HMA surface lift and 3 inches or 0.25 feet (76.2 mm) HMA leveling lift.
- Section 7 - Good bond between 5 inches or 0.42 feet (127 mm) HMA overlay and HMA pavement except one corner of the section (lower left side) had extended simulated stripping condition from Section 6.

The test results in Figure 6 (Section 1) indicate likely debonding between depths of 4.8 and 6 inches or 0.4 and 0.5 ft (121.9 and 152.4 mm). The interpretation of the SASW test results agree well with the as built condition of Section 1. The test resutls in Figure 7 (Section 6) indicate debonding from measurement Grid Lines 9 and 10 at the shallow depth of 1.2 – 2.4 inches or 0.1 – 0.2 ft (30.5 – 60.96 mm). The SASW test results also agree well with the actual built in condition of Section 6. Last, the test results of Figure 8 (Section 7) are indicative of sound pavements except at the lower left corner (a few test locations) where the test results show a shallow delamination between 1.2 and 2.4 inches or 0.1 and 0.2 ft (30.5 – 60.96 mm). This finding again agrees well with the as-built conditions of Section 7 where the majority of the section is sound except one corner where the stripping condition was accidentally extended from Section 6.

CONCLUSIONS

The Spectral Analysis of Surface Waves method can be effectively used to identify the bonding conditions of multi-layer HMA pavements. The IE/SASW Scanner accelerates the testing process by allowing up to three scan lines to be tested at once in a rolling system traveling approximately 1 mph. The system can be attached to either a vehicle or a hand cart. An important finding from the research project was the determination that a significant drop in the surface wave velocity in the dispersion curve is a good indication of debonding between layers of HMA pavement layers. The dispersion curve also indicates the approximate depth at which the debonding occurs, which is valuable information for assessing repair alternatives.

REFERENCES

1) Van Dam, T., K. Kirchner, M. Shahin, and E. Blackmon. Consequence of Layer Separation on Pavement Performance. Report DOT/FAA/PM-86/48. U.S. Department of Transportation, Federal Aviation Administration, Washington, DC, April 1987.
2) Ziari, H. and M. Khabiri. Interface Condition on Prediction of Flexible Pavement Life. Journal of Civil Engineering and Management, Vol. 13, No. 1, 2007, pp. 71-76.
3) Tinkey, Y and Olson, L.D. Vehicle Mounted Bridge Deck Scanner. NCHRP-IDEA Program Final Report (NCHRP-IDEA Contract 132), 2010.
4) Tinkey, Y, Olson, L.D., Miller, P and Tanner, J. Vehicle Mounted Bridge Deck Scanner. Proceedings of Transportation Research Board, Washington DC, January 2011.
5) Stokoe, K. H., II, Nazarian, S, Rix, G.J., Sanchez-Salinero, I., Sheu, J.C. and Mok, Y.J.. In Situ Seismic Testing of Hard-to-Sample Soils By Surface Wave Method. Proceedings, American Society of Civil Engineers, Specialty Conference on Earthquake Engineering and Soil Dynamics II- Recent Advances in Ground Motion Evaluation, Park City, Utah, 1988, 264-278.
6) Aouad, M. F., Stokoe, K. H., and Roesset, J.M. Evaluation of Flexible Pavements and Subgrades using the Spectral Analysis of Surface Waves Method. Publication Research Report FHWA/TX-95+1175-7F, Texas Department of Transportation.