NDT-CE 2022 - The International Symposium
on Nondestructive Testing in Civil Engineering
Zurich, Switzerland, August 16-18, 2022

Fusion of NDE Scanning and Photogrammetric Data for Concrete Bridge Decks and Girders Condition Assessment

Larry D. OLSON[1]*

[1] Olson Engineering, Inc.; Wheat Ridge, Colorado, USA
*Corresponding author, e-mail address: Larry.Olson@OlsonEngineering.com

Abstract

The first case history presents 3-D results of Impact Echo (IES) and Ground Penetrating Radar (GPR) scanning plus Spectral Analyses of Surface Waves (SASW) tests of post-tensioned concrete bridge girders. The NDE results were overlaid on photogrammetric images of visible corrosion/cracking damage to the concrete bridge girders of an aging bridge due to de-icing salts and a marine environment. Cart-based scanning results from GPR and Impact Echo are presented next for a bare concrete deck to map both top and bottom delaminations and depth of concrete cover. The nondestructive evaluation (NDE) results are overlaid on photogrammetric images of the bare concrete deck to visibly compare areas of spalling, delamination and deck patching for improved interpretation, visualization and mapping of internal deck delaminations and other concrete damage. The NDE and photogrammetric data fusion approach combine to provide more accurate surface and full-depth images of bridge deck conditions for repair designs.

Keywords: radar, impact echo, scanning, photogrammetry, data, fusion, imaging, concrete, bridges, decks, girders

1 Introduction

Concrete repair projects are increasingly benefitting from the use of nondestructive evaluation (NDE) methods to diagnose and identify where internal concrete conditions are in need of repair *[1]*. The International Concrete Repair Institute's ICRI 210 Evaluation Committee has produced two technical guidelines involving NDE: ICRI 210.4 Guide for Nondestructive Evaluation Methods for Condition Assessment, Repair, and Performance Monitoring of Concrete Structures *[2]* and ICRI 210.1R Guide for Verifying Field Performance of Epoxy Injection of Concrete Cracks *[3]* which reference and discuss the NDE methods included in this paper. Once flawed/damaged conditions are identified from NDE, destructive drilling/coring along with video borescopes are used to determine the nature of the anomaly and choose repair methods and materials. By taking multiple, high-resolution digital photographs at different angles and using photogrammetry to process the photos, a high-resolution image is produced with minute detail for the current concrete surface distress conditions. Photogrammetric images also provide an important baseline against which to evaluate the progression of surface distress over time. The overlay of NDE data on photogrammetric images of concrete surface conditions is known as data fusion and can be done in a 2-D/3-D fashion. Data fusion is being increasingly performed to provide engineers and repair contractors with a better understanding of visible surface conditions integrated with internal concrete conditions for concrete repair projects. Case histories are presented below for concrete bridge girders and concrete bridge decks to illustrate NDE and photogrammetric data fusion.

2 Data Fusion for Concrete Bridge Girder Condition Assessment

The use of the data fusion approach is discussed below for evaluation of concrete bridge girders using photogrammetry along with the NDE methods of ground penetrating radar (GPR), impact echo scanning (IES) and spectral analyses of surface waves (SASW). The post-tensioned, pre-stressed and reinforced concrete bridge girders are from an older bridge and subject to chlorides exposure and corrosion over time.

2.1 Photogrammetry

The need for concrete repairs generally arises when surface distress is visually noted. Photogrammetry was used to provide detailed images of concrete distress conditions of bridge girders for fusion with NDE results and to evaluate the progression of surface distress over time with subsequent photogrammetric studies. The first step is to capture raw photographic digital images with a high-resolution phone camera at a minimum; however, a telephoto lens digital camera is useful for larger structures. Camera orientations are then determined and multiple overlapping photographs taken at different view angles (overlapping) with identifiable features for image processing. There are a number of commercial and shareware software packages available for photogrammetric image analyses that can be used to generate 2-D and 3-D model images. An example photogrammetric bridge girder image with high-resolution (0.025 to 0.04 inch [0.6 to 1 mm]) images took 3-4 hours of processing time on a computer with a very good GPU video processor (Fig. 1).

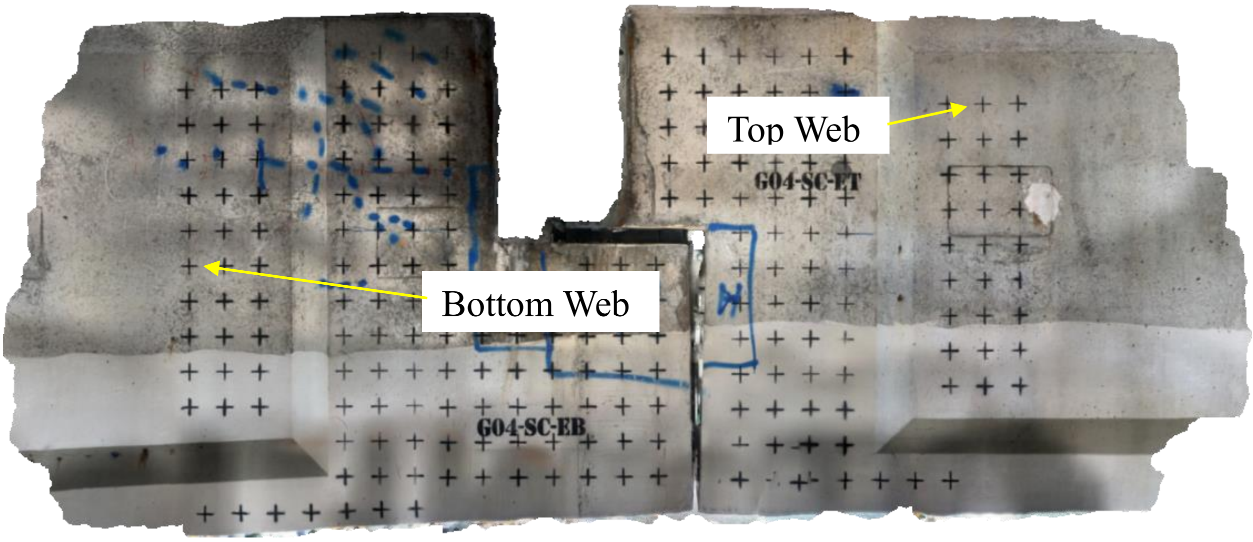

Figure 1: Digital photogrammetry image for bridge girders with 6-inch (150 mm) NDE grid marked out on girder webs and ends (note "3-D" like depth effect in image)

2.2 Ground Penetrating Radar (GPR)

The GPR method involves moving an antenna across a test surface while periodically pulsing the antenna and recording the received echoes (Fig. 2). A handheld GPR unit was used to scan the girder webs and ends both vertically and horizontally (Fig. 3) in order to produce 3-D images

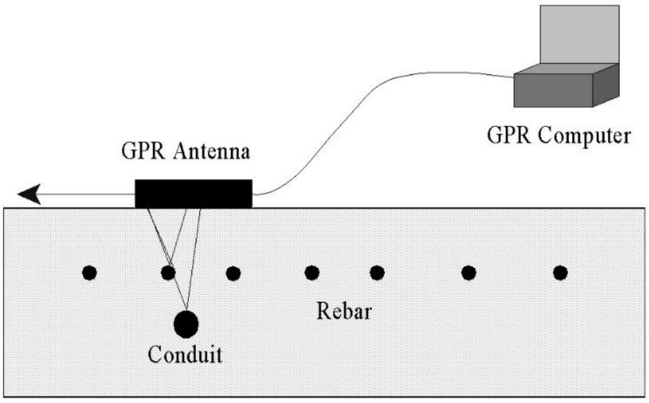

Figure 2: Ground penetrating radar (GPR) scanning.

of embedded pre-stress, post-tensioning ducts, reinforcement, and steel plates in the girders. The raw GPR data from a vertical 2-D straight scan line is presented in Figure 4(a) with the hyperbolic-shaped reflections at a 2 in (50 mm) concrete cover depth indicating the near-surface horizontal rebar. Note the post-tensioned metal tendon ducts are larger in diameter and have broader and deeper hyperbolic reflections at 3 to 4 in (75 to 100 mm) deep. The GPR data is then migrated to collapse the rebar and duct reflections to a dot shape as shown in Figure 4(b). The final step is a Hilbert Transform that further clarifies the depths and locations of the rebars as the pulses are merged into a single pulse envelope as shown in Figure 4(c). The horizontal and vertical processed 2-D GPR scans were then combined to produce the 3-D GPR image that is overlaid on the photogrammetric image (Fig. 5). Review of this figure reveals the locations of embedded rebar, tendon ducts and metal plates overlaid on the photogrammetric image in Figure 1.

Figure 3: Horizontal GPR scanning on a 3 in (75 mm) grid (vertical scans were also completed) for 3-D GPR image

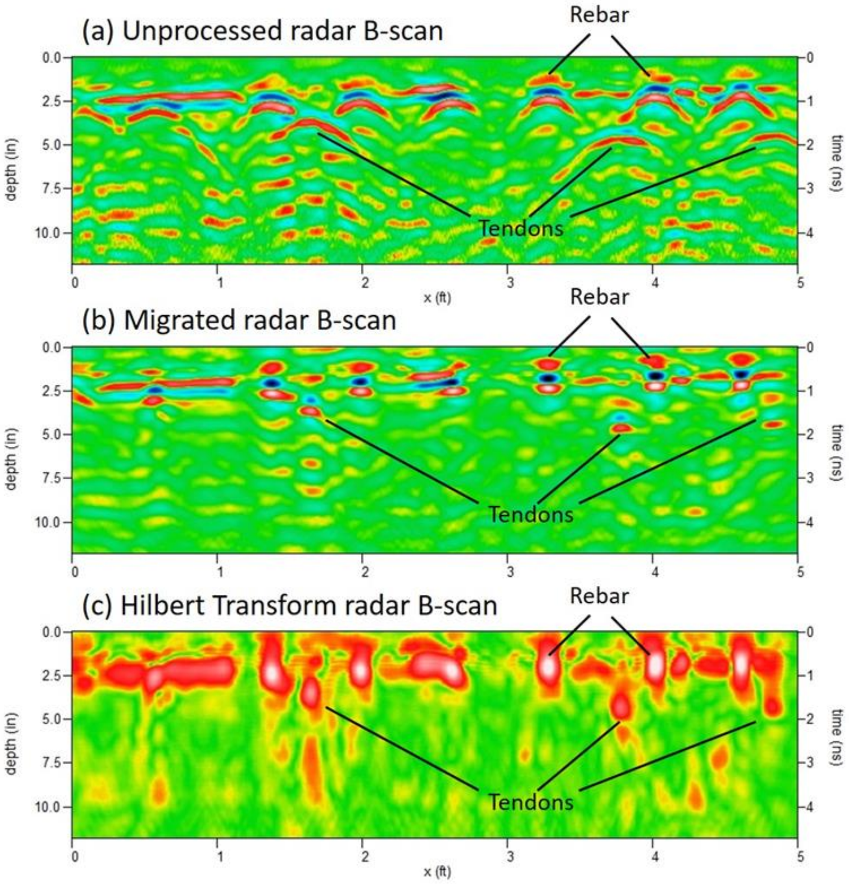

Figure 4: 2-D GPR vertical scan data analyses steps before combining into 3-D GPR image

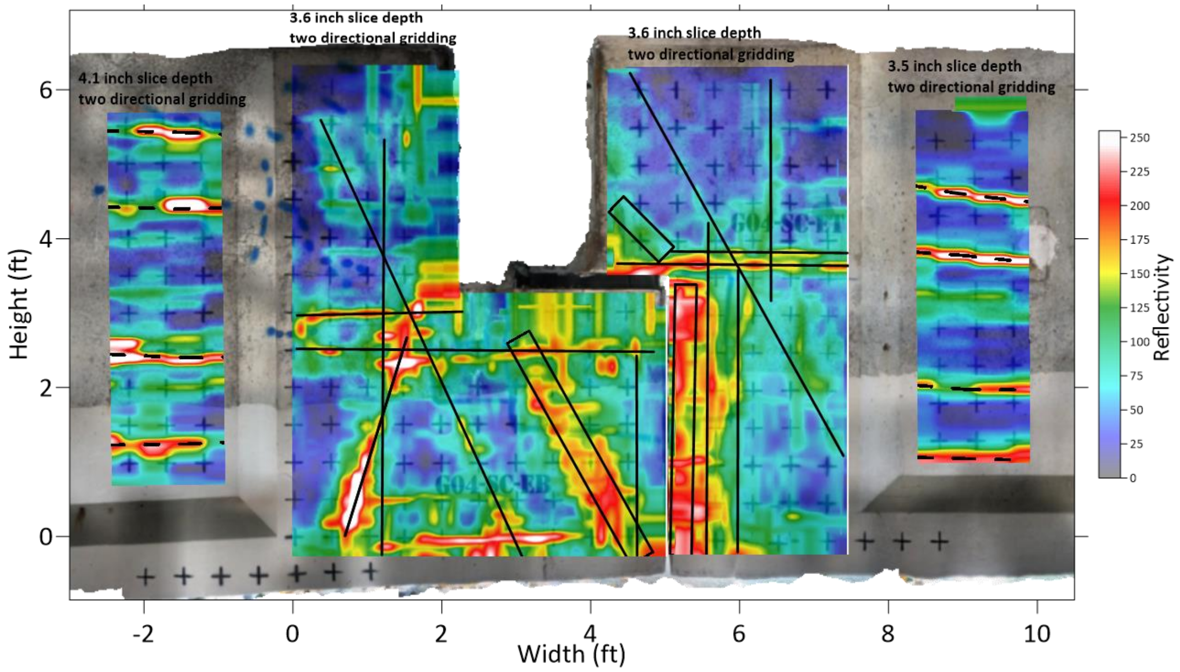

Figure 5: Data fusion – 3-D GPR depth slices for PT ducts, rebar and embedded plates

2.3 Impact Echo Scanning (IES)

The impact echo test method is ASTM Standard C1383-15 *[4]* and based on impacting the concrete and recording the resulting compressional wave echoes with a receiver in the time domain and analyzing the time data to obtain the resonant echo frequency with a Fast Fourier Transform (Fig. 6). The bridge girders were tested with an impact echo scanner that consisted of a rolling displacement transducer/solenoid impactor scanner system that covers more testing area in less time with a test every 1 in (25 mm) on vertical scan lines spaced 6 in (150 mm) apart (Fig. 7). The IES unit was used to check the concrete thickness/integrity and to detect voided vs. grouted post-tensioned tendon duct conditions in the web walls. Sound concrete web wall and grouted duct conditions are shown on a thickness echo plot on the left in Figure 8. Sound concrete web wall with a poorly grouted/void tendon duct condition are indicated by the increase in thickness echo on the right in Figure 8.

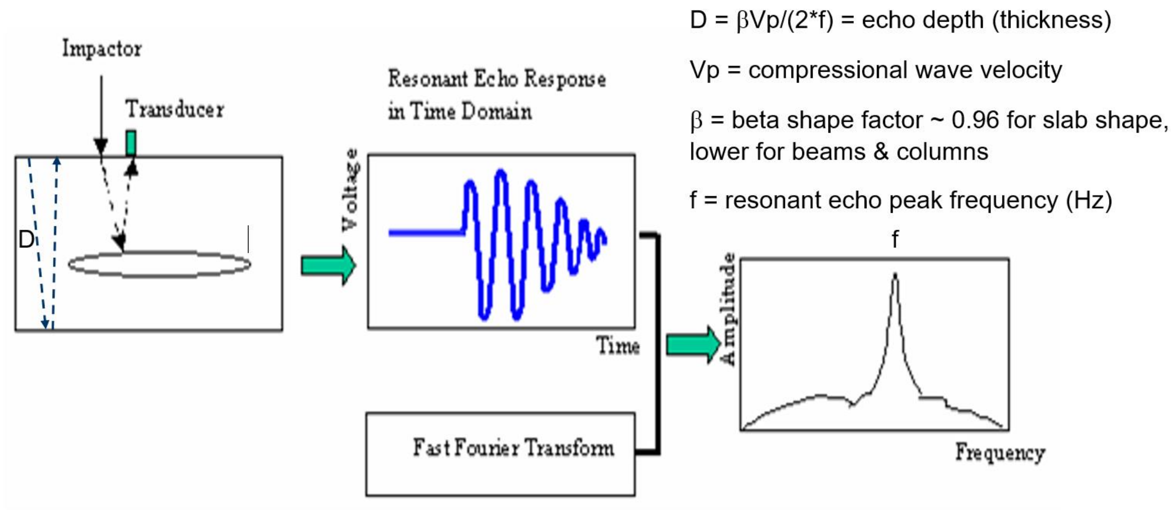

Figure 6: Impact echo test method and data analysis steps

Figure 7: Impact echo scanner with rolling transducer wheel and solenoid impactors (left) and impact echo scanning of girders on vertical lines at 6 in (150 mm) spacing (right)

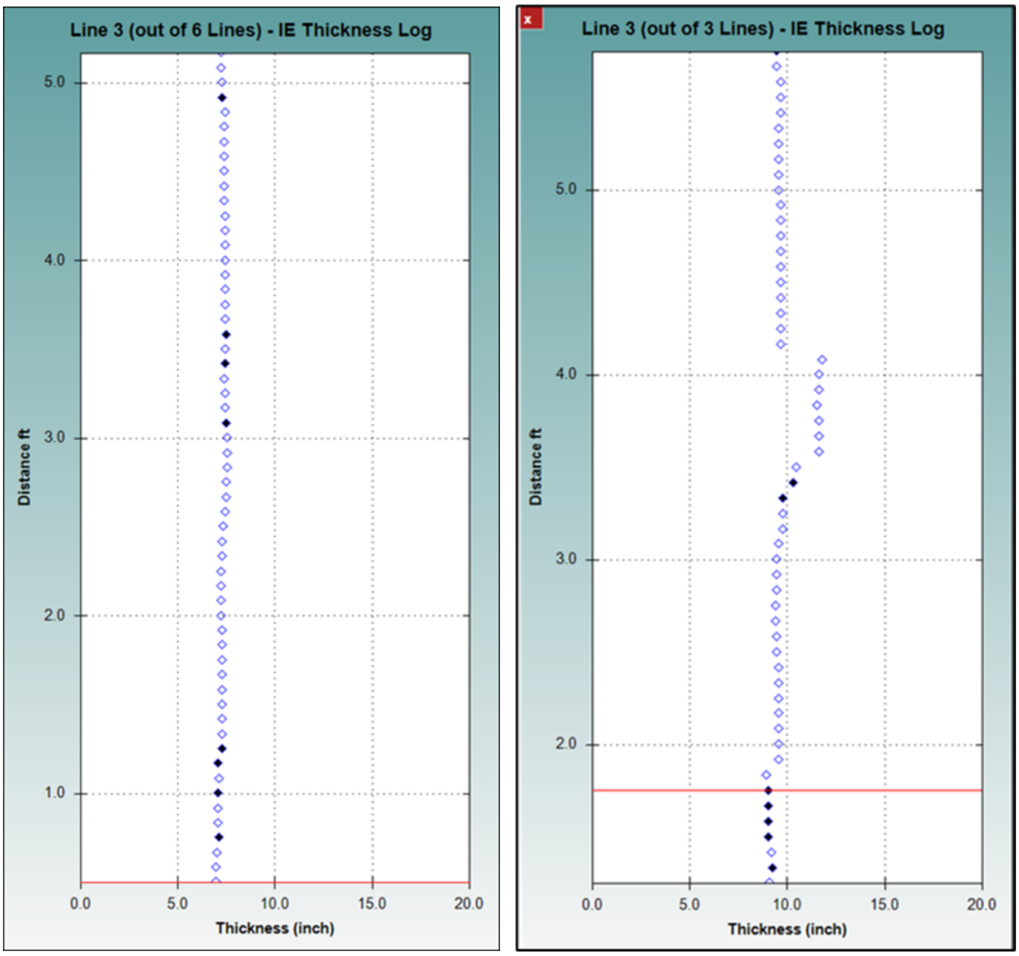

Figure 8: Vertical scan IES results of approximately 7.5 in (190 mm) thickness echoes for sound web wall with grouted tendon ducts (left) and poor/void tendon duct grouting conditions shown by increase in echo thickness from 8 to 9 in (200 to 225 mm) to 12 in (300 mm) at 3.6 to 4.1 ft (1.1 to 1.25 m) (right)

2.4 Spectral Analyses of Surface Waves (SASW)

The SASW method measures the propagation speed of surface waves with various wavelengths (Fig. 9) for tests across a crack to determine its depth. Short wavelength waves sample shallow, longer wavelengths sample deeper and surface wave velocity = frequency x wavelength. SASW testing allows the measurement of the velocity profile versus depth into the structure, which can be related to the strength and condition of the concrete versus depth and the depth/extent of cracking damage. Refer to the ACI 228.*2R[5]* report on Nondestructive Test Methods for Evaluation of Concrete in Structures for detailed information on the SASW, IE and GPR methods. SASW velocity vs. wavelength plots (dispersion curves) are presented for sound concrete on the left in Figure 10 and for cracked concrete on the right in Figure 10. Review of these plots indicates a crack depth extending to about 7 to 8 in (175 to 200 mm) deep in the right plot where the surface wave velocity increases.

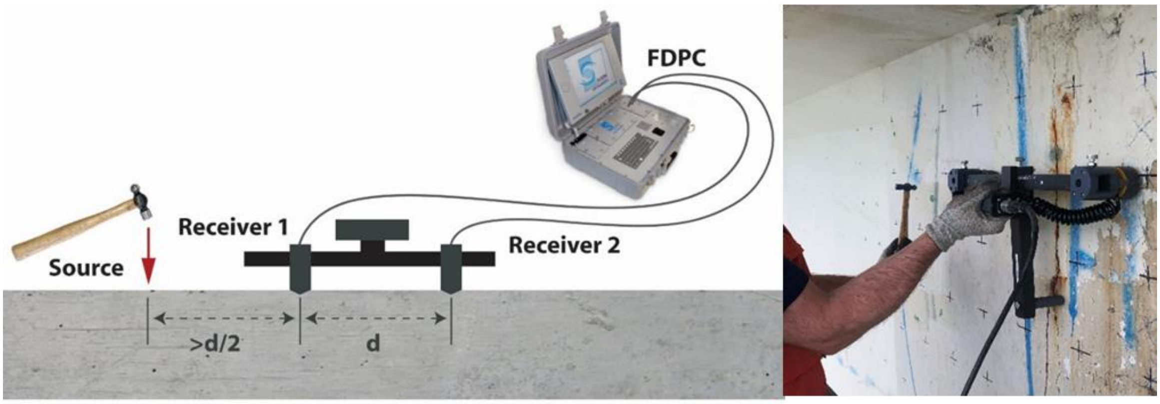

Figure 9: Spectral analysis of surface waves method (SASW) and SASW bar with 2 receivers testing across surface-opening crack on girder

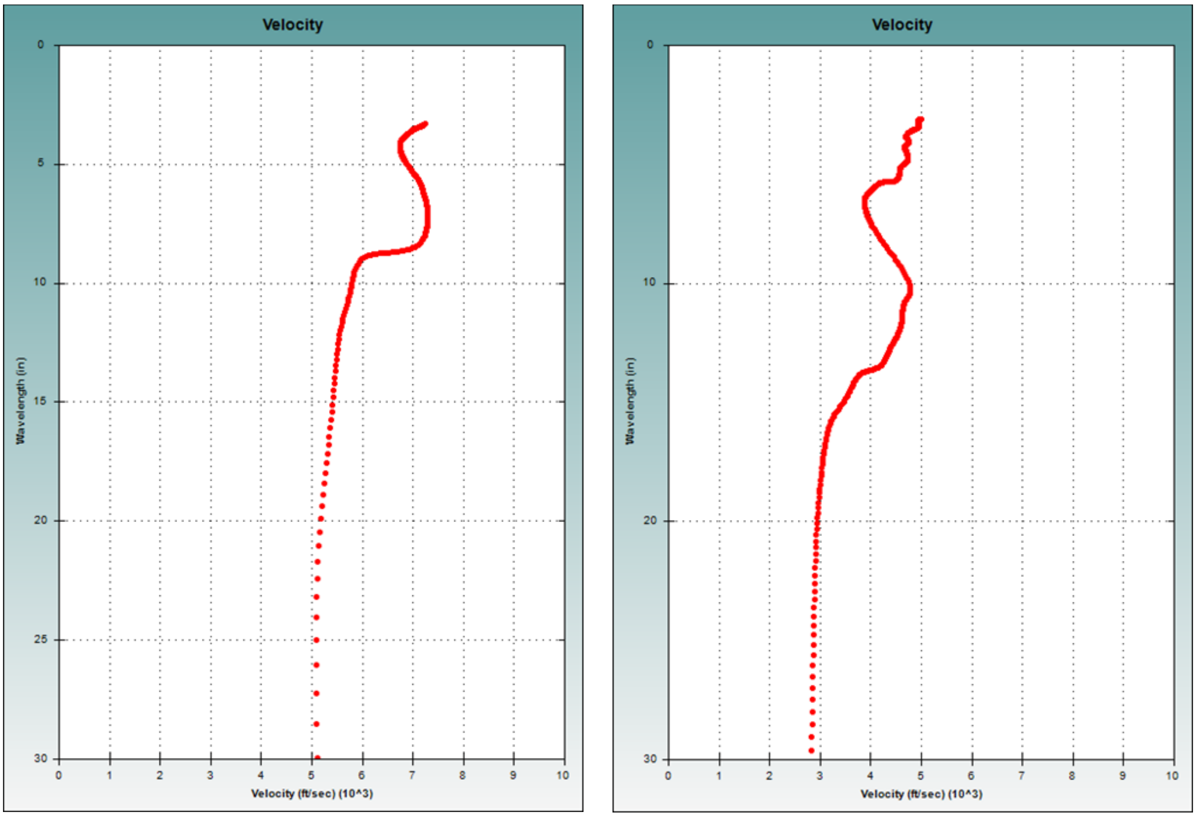

Figure 10: SASW velocity vs. wavelength results on sound (left) and visibly cracked (right) girder areas. The backside of the sound 7.5 in (190 mm) thick web section is shown by the drop in surface wave velocity from approximately 7,000 ft/s from 4 to 8 in (100 to 200 mm) to approximately 5,500 ft/s at a wavelength of 8 in (200 mm) (left). The SASW test across a crack on a girder end indicates a crack depth from the surface to approximately a 7 to 8 in (175 to 200 mm) depth where the surface wave velocity increases (right)

2.5 Data Fusion of Photogrammetric Images and NDE Results on Bridge Girders

The IES and SASW results were fused (overlaid) onto the photogrammetric image (Fig. 11) along with the GPR 3-D locations of the tendon ducts. Review of this figure provides combined data as to where the tendon ducts are (from GPR) and their grout conditions (from IES) plus crack depth data (SASW colored circles) and the surface conditions of the photogrammetric image for the web walls. An overall fusion image plot for the girder end walls of the IES and SASW results is presented in Figure 12. Note that this figure provides combined data as to the locations and depths of shallow to deep delaminations (from the IES results) along with crack depth data (SASW colored circles) and the surface conditions of the photogrammetric image.

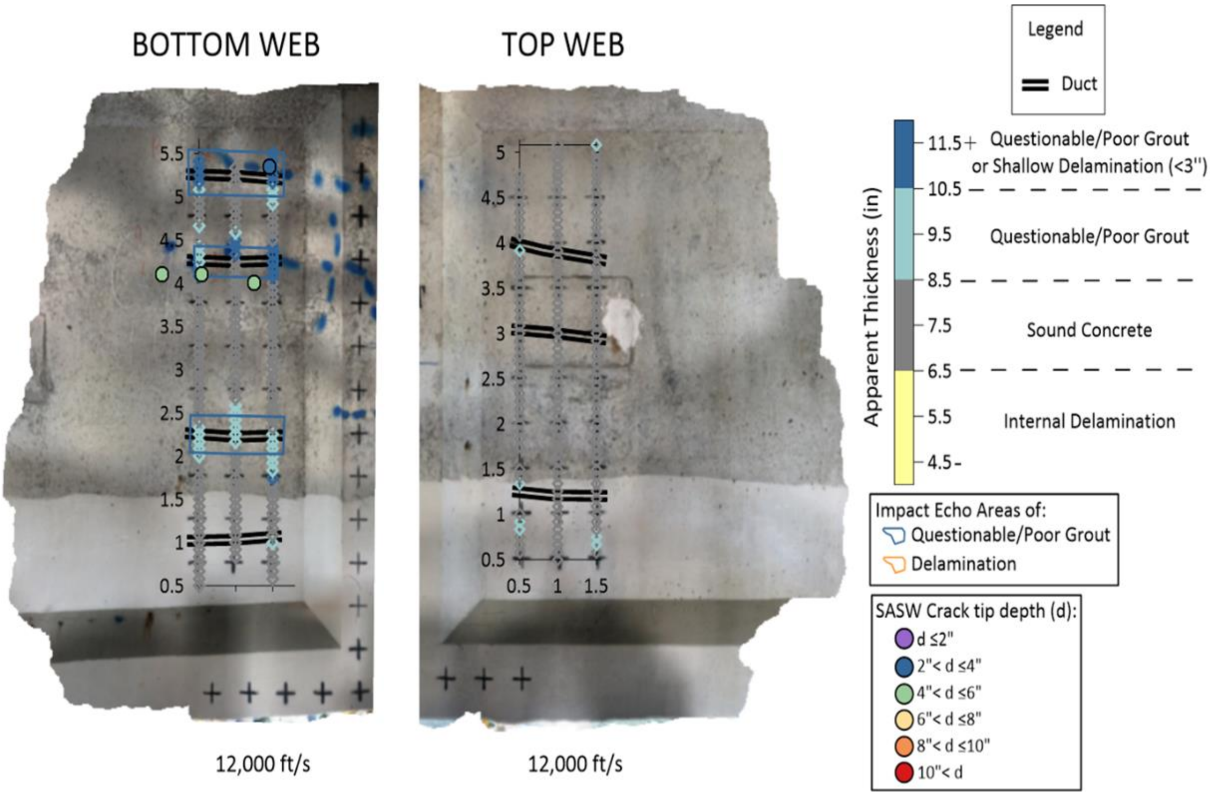

Figure 11: Data fusion of photogrammetric images, impact echo scanning, SASW and GPR results for duct grouting, crack tip depth and duct locations for web walls

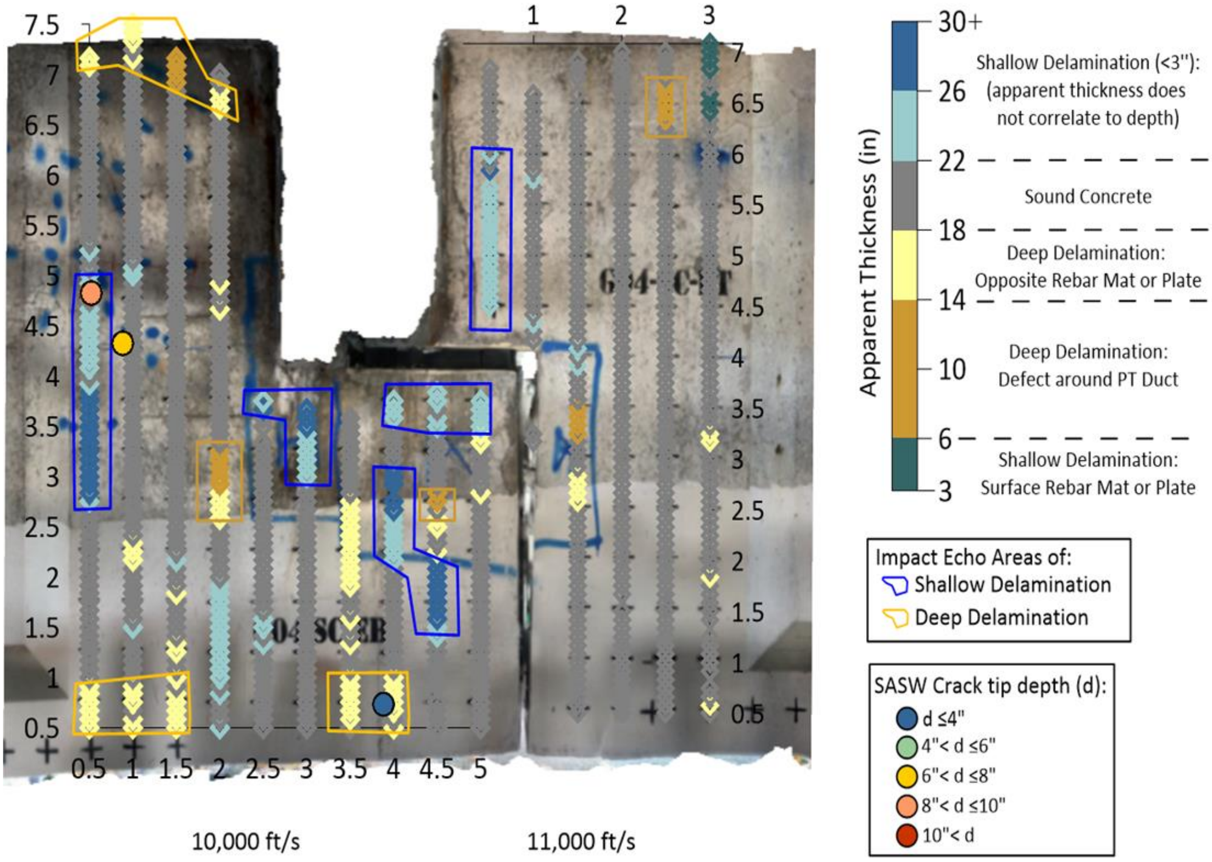

Figure 12: Data fusion for girder end walls of photogrammetric images, impact echo scanning, SASW and GPR results for duct grouting, crack tip depth and duct locations

3 Data Fusion for Concrete Bridge Deck Condition Assessment

The use of the data fusion approach is discussed below for evaluation of a concrete bridge deck using photogrammetry along with the NDE methods of ground penetrating radar (GPR), and impact echo scanning using an Olson Instruments Sonic Surface Scanner (SSS-IE). The cast-in-place concrete deck was evaluated for rebar depth with GPR in conjunction with the SSS-IE data to identify areas of delamination and internal horizontal cracking, and NDE results were overlaid on photogrammetric images.

3.1 Photogrammetry

The photogrammetry approach is described above in Section 2.1. The process is the same for bridge girders and bridge decks. A photogrammetric image of the bridge deck is presented in Figure 13 below.

Figure 13. Digital orthomosaic (photogrammetric image) of concrete bridge deck

3.2 Ground Penetrating Radar (GPR)

The GPR in this study utilized a cart that was rolled along longitudinal scans lines at the same 1-foot transverse spacing across the entire bridge (same configuration as SSS-IE discussed below – both systems configured with integrated RTK GPS systems for centimeters-accurate location data). The GPR and SSS-IE systems are shown side-by-side in Figure 14. The GPR data were used to develop a detailed 2-D steel reinforcement concrete cover map to be constructed. Figure 15 presents an example raw GPR data scan from the bridge deck showing the transverse steel reinforcing bars denoted with a red dot. Figure 16 presents the resulting interpolated concrete cover map overlaid on photogrammetric image.

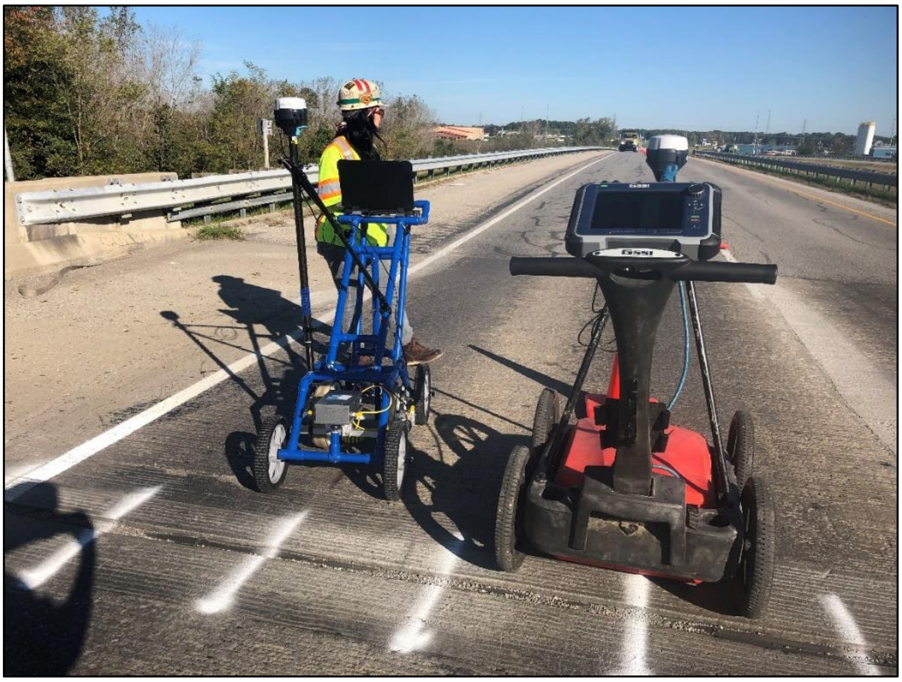

Figure 14: Photograph of Olson Sonic Surface Scanner – Impact Echo system (left) and of the GSSI SIR-4000 computer and a 1600 MHz GPR antenna (right) placed in a hand push-cart for ground coupling. Note GPS unit antennas (white) sticking up above each cart

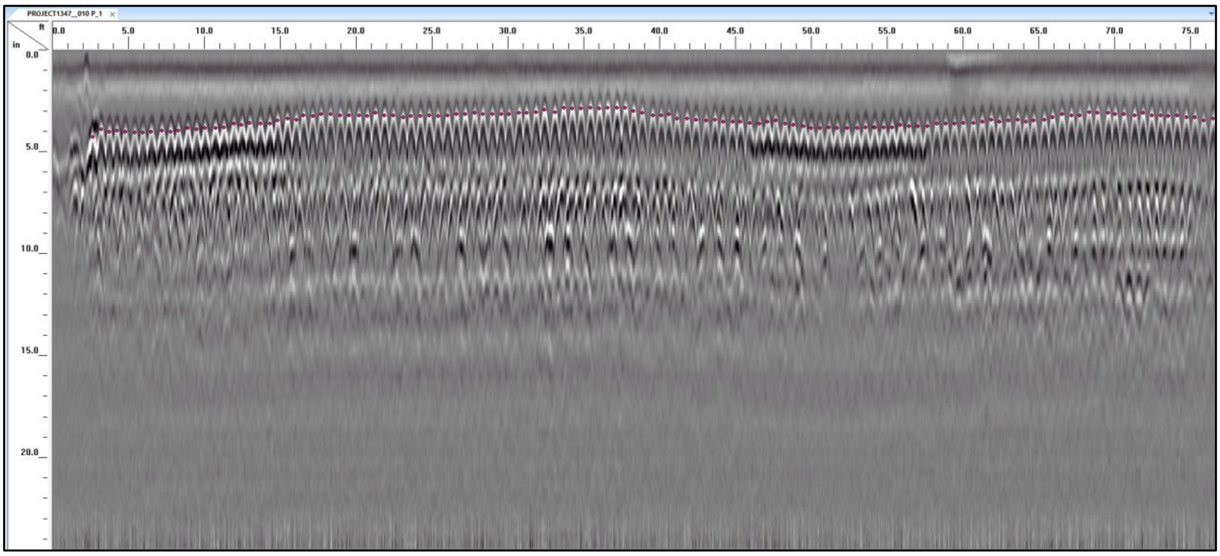

Figure 15: Example raw GPR scan with the transverse rebar hyperbolic-shaped reflections, each denoted with a red dot.

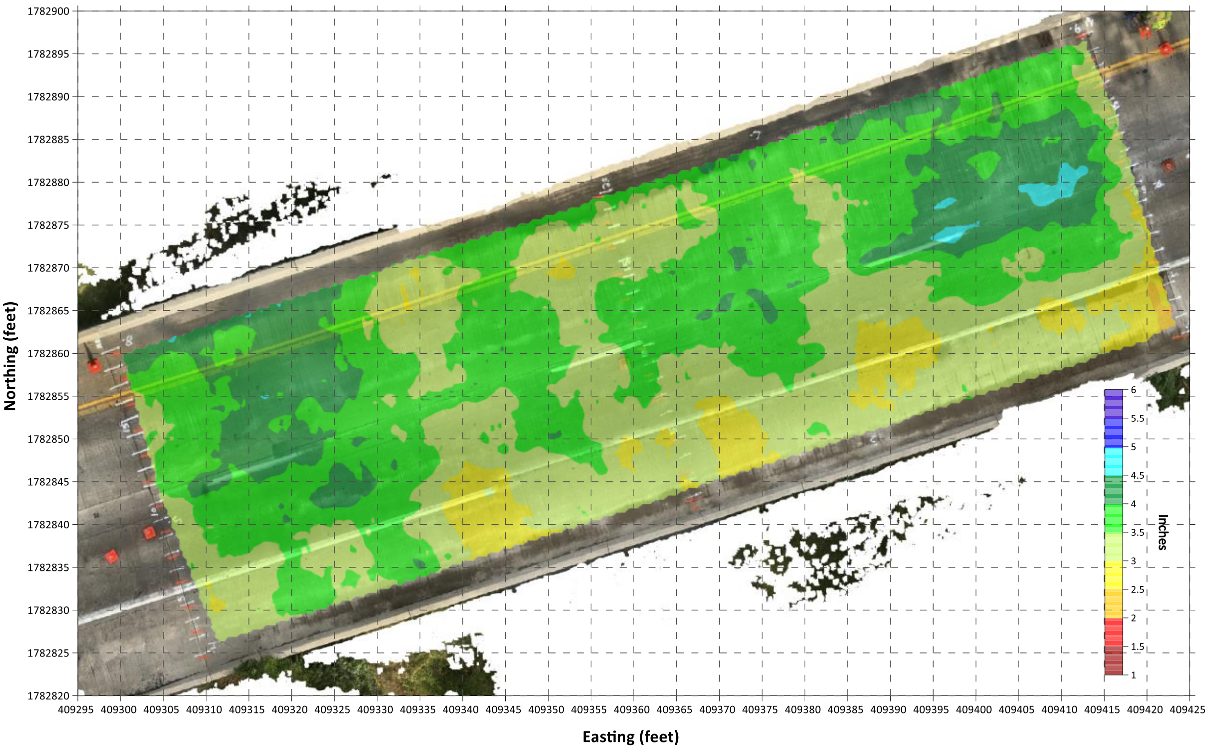

Figure 16: GPR-based Rebar Cover Depth Interpolated Map with photogrammetry underlay and 50% data transparency.

The GPR attenuation plot at the 30% low amplitude level is presented in Figure 17. Based upon the S^3-IE results discussed in the next section below, the 30^{th} percentile cut-off value map to be the most accurate representation of deck conditions. The GPR results are in general agreement with the S^3-IE results and indications widespread delamination throughout the bridge deck.

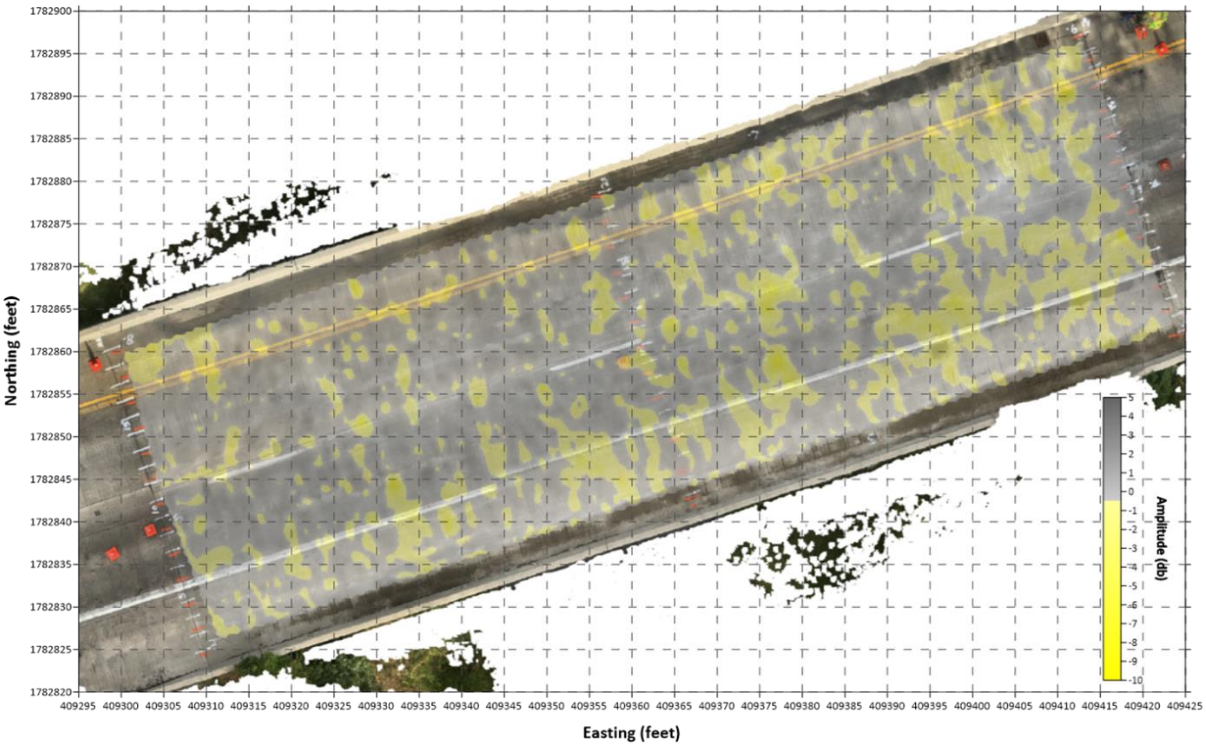

Figure 17: **GPR-**based Rebar Amplitude Interpolated (smoothed) Condition Map with photogrammetry underlay and 50% data transparency. Cut-Off value = 30th Percentile of Data Envelope indicating likely corrosion areas.

3.3 Sonic Surface Scanning – Impact Echo (SSS-IE)

The SSS-IE method uses the same IES method discussed in Section 2.3, but with an Olson Instruments Sonic Surface Scanner that performs an IE test on two scan lines every 6 inches as the unit is rolled along the bridge deck at a rate of approximately 1.0 mph (1.6 km/h). A close-up view of this system is presented in Figure 18. Scan lines were spaced 1 foot (0.3 m) apart across the entire width of the bridge, along the same lines as the GPR discussed above. For bridge deck studies, results are typically presented based upon the thickness of the resulting resonant echo. If near-surface delaminations within the concrete slab are present in typically the top 3 inches of the concrete, the delaminated concrete responds with a low-frequency, undamped flexural resonance response which counter-intuitively appears much thicker than the expected deck thickness and corresponds to the hollow, drummy sound associated with acoustic sounding. The actual depth of such a delamination is not determinable from the data but is generally assumed to be at the depth of the deck top-steel or the interface of an overlay. If the concrete is sound near the surface but has other deeper internal horizontal cracking, then an echo resonance is measured that corresponds to the depth of that internal cracking, which may be delaminations due to deep top steel, or could be delaminations at the bottom of the deck due to corrosion of bottom steel. If no damage is present, the IE tests exhibit sharp and consistent resonant echo frequencies that correspond to the concrete deck thickness at that test point. An example of this data is presented in Figure 19. A map of the SSS-IE results is presented in Figure 20.

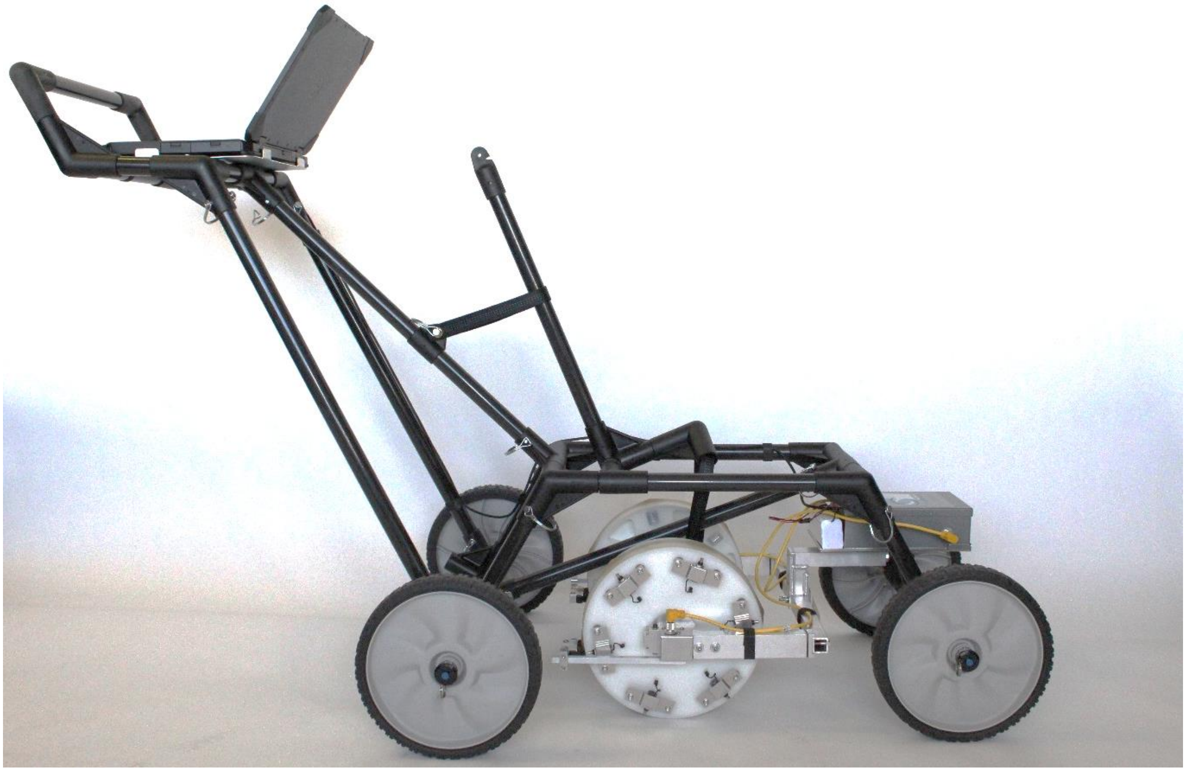

Figure 18: Sonic Surface Scanner (SSS) for slow-rolling Impact Echo and Surface Waves Scanning of Concrete Decks/Slabs and Asphalt Pavements with tests every 6 inches (~150 mm) – note solenoid impactors on sides of sensor wheels and brass displacement transducers on wheel surface.

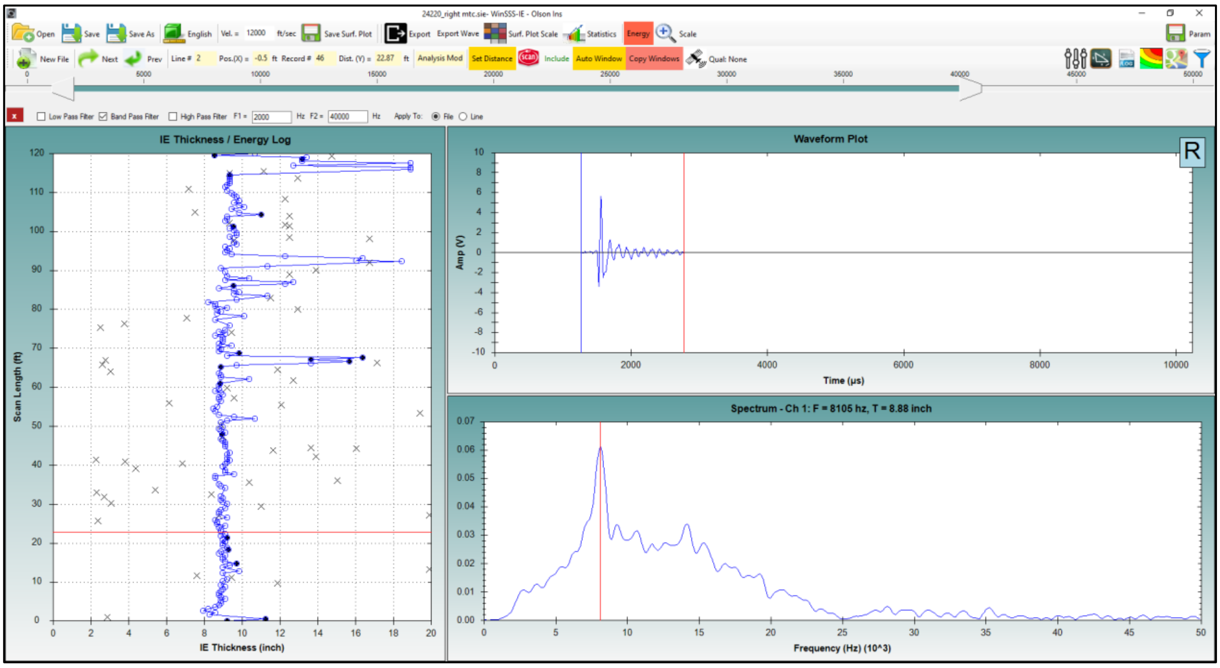

Figure 20. SSS-IE line along a bridge deck with all data for the line (thickness vs distance – left) and time and frequency domain for the individual result at the cursor location. “Spikes” in the data (apparent higher thickness echoes) on the left plot of dominant echo depth vs. distance show areas where near-surface delaminations are inferred for one of the sensor wheels.

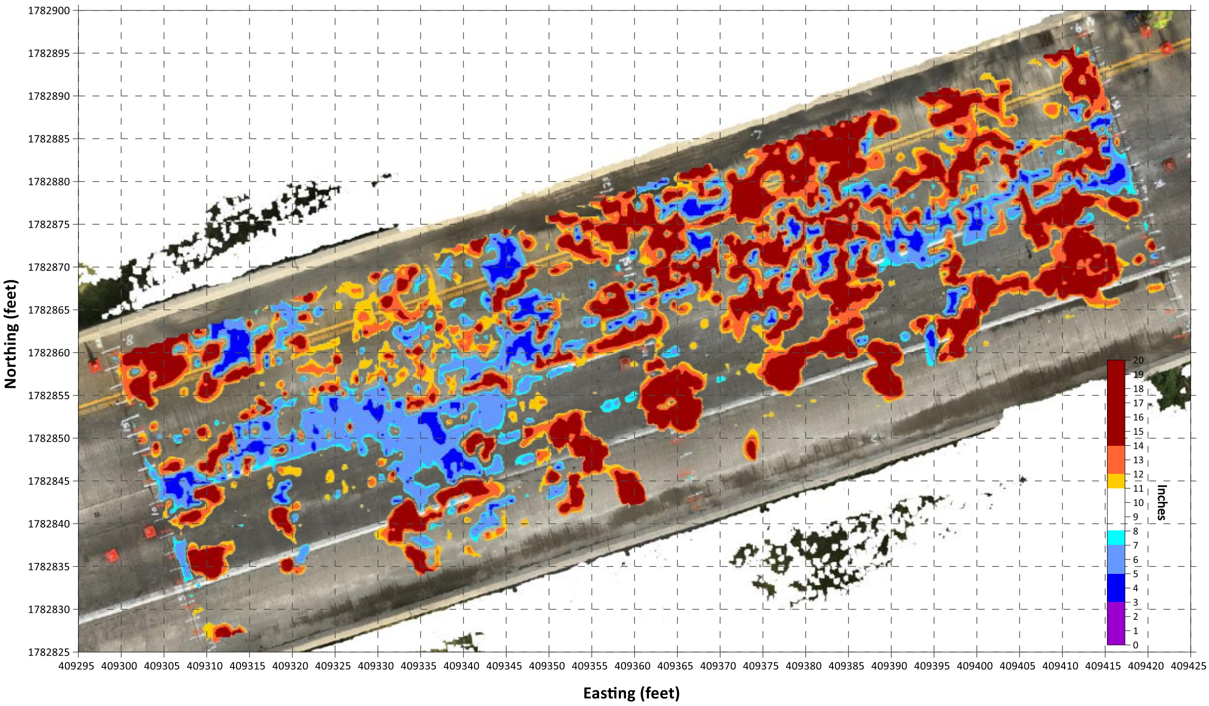

Figure 19. SSS-IE Interpolated Condition Map (presented as thickness echo depths – see legend on right) with photogrammetry underlay.

4 Summary of Data Fusion with Photogrammetric and NDE Methods

Photogrammetry provides detailed imaging with 3-D like depth views of concrete surface conditions for overlay of NDE results and future comparisons of how surface distress is advancing. The use of Ground Penetrating Radar (GPR) can image complex (or simple) reinforcement, PT duct and metal plate embedment conditions. Impact Echo Scanning (IES/SSS-IE) identifies grouted vs. voided Post-Tensioning Duct conditions and delamination/cracking conditions in concrete. Spectral Analyses of Surface Waves (SASW) provides data on depth of cracking and concrete integrity as well as one-sided velocity measurements. Finally, data fusion integrates internal concrete conditions from NDE with photogrammetric surface concrete images for clearer structural assessment and comparison of structural concrete conditions.

References

[1] Larry Olson, ‘Fusion of Nondestructive Testing and Photogrammetry for Concrete Condition Imaging’, Concrete Repair Bulletin July/August 2021, Vol. 34, No. 4, International Concrete Repair Institute, 2021.

[2] 210.4R-2021 – ‘Guide for Nondestructive Evaluation Methods for Condition Assessment, Repair, and Performance Monitoring of Concrete Structures’, International Concrete Repair Institute, 2021.

[3] 210.1R-2016 – ‘Guideline for Verifying Field Performance of Epoxy Injection of Concrete Cracks’, International Concrete Repair Institute, 2016.

[4] ASTM C1383-15 – ‘Standard Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method, ASTM International, 2015.

[5] ACI PRC-228.2-13 – ‘Report on Nondestructive Test Methods for Evaluation of Concrete in Structures’, American Concrete Institute, 2013.