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VISUALIZATION AND INTERPRETATION OF IMPACT ECHO DATA FROM BRIDGE DECK TESTING

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ABSTRACT

Accurate assessment of the condition of bridges leads to their economic management. Ultrasonic seismic methods can be successfully used for this purpose by evaluating changes in material characteristics and detection of development of defects and zones of deterioration. The impact echo method is of special benefit in evaluation of corrosion induced deck delamination, due to its nondestructive nature, speed of evaluation and ability to detect delaminated zones at various stages of deterioration: from initial to progressed and developed. The traditional approach in condition assessment of bridge decks by impact echo based on review of individual test point records, and a new automated approach based on three dimensional data visualization are presented. The developed three dimensional visualization platform allows both the advanced presentation and interpretation of impact echo data. The data presentation is provided in terms three dimensional translucent visualizations of reflectors in a bridge deck section, and horizontal and vertical cross sections through all distinctive zones, including a zone of delamination. The associated interpretation platform allows both the overall assessment of the condition of the deck, through cumulative distributions and histograms of reflection intensity, and identification of deteriorated zones of the deck for repair or rehabilitation in an efficient and intuitive way. The visualization platform effectively enables an impact echo device to be used as some kind of a bridge deck sonar device.

INTRODUCTION

The condition of the transportation network in the United States is deteriorating and requires enormous financial and human resources for its maintenance and mitigation. According to the National Bridge Inventory (NBI) (Federal Highway Administration, 2004), about 25.4% out of 600,000 bridges in the United States are structurally deficient or obsolete. An important component of the inspection and rehabilitation of concrete bridges is the assessment of the bridge's deck condition, whether the deterioration manifests itself through material degradation or defect generation. One of the most common problems in concrete bridge decks is a corrosion induced deck delamination. The current practice of deck inspection by chain dragging can be described as nondestructive and relatively rapid. However, the accuracy of chain dragging is significantly compromised by the fact that it can only be used to identify delaminations at stages where the deterioration has already progressed to such an extent that major rehabilitation measures are needed. The advent of nondestructive evaluation techniques has significantly aided this task, and several methods have been successfully utilized to detect common defects in concrete bridge decks. Among these methods, ultrasonic seismic techniques are one of the most widely used techniques.

Impact echo (IE), together with other ultrasonic seismic techniques, like ultrasonic body-wave (UBW) and ultrasonic surface-wave (USW), has been successfully implemented in comprehensive evaluation of bridge decks *(1, 2, 3)*, in short and long term monitoring of pavement materials *(4,5)*, and in evaluation of other infrastructure systems *(6)*. It has been demonstrated that IE can detect and assess delaminations at various deterioration stages. While it is capable of detecting deck delaminations at various stages of deterioration progression, precise interpretation of the measured parameters has yet to be fully automated. Significant improvements to the automation of the evaluation process are expected to come from neural network algorithms developed using finite element simulations of ultrasonic testing on delaminated bridge decks *(3)*, and improved data visualization.

An impact echo data visualization and interpretation framework for the assessment of concrete bridge decks is discussed in this paper. The first part of the paper discusses fundamental aspects of impact echo testing in bridge deck evaluation, its implementation in the field using one of the integrated ultrasonic seismic devices, the Portable Seismic Property Analyzer (PSPA), and the current data analysis and interpretation approach. Field implementation impact echo is illustrated using results from testing on two bridge decks in Virginia. The second part of the paper discusses IE data visualization and to it related interpretation techniques, which can be used to both enhance and simplify the interpretation of results of testing on delaminated bridge decks. Finally, the proposed data visualization provides practicing engineers a more intuitive approach to bridge deck evaluation, by effectively enabling IE devices to act as some kind of bridge deck sonar devices.

## BRIDGE DECK CONDITION ASSESSMENT BY IMPACT ECHO

IE method is an ultrasonic seismic method that is in the case of bridge deck evaluation, often used in conjunction with other ultrasonic seismic methods. The following sections discuss the ultrasonic seismic methods typically used in bridge deck evaluation, their field implementation, explanation of the rationale behind the condition grading system, and the current practice of data presentation.

Ultrasonic Seismic Methods for Bridge Deck Testing

Seismic methods enable the evaluation material properties and structural defects by measuring the velocity of propagation of elastic waves and by observing various wave propagation phenomena, such as reflections, refractions and dispersions. Of particular interest for bridge deck evaluation are three ultrasonic techniques: UBW, USW and IE. UBW and USW techniques are used to measure velocities of propagation of compression (P) and surface (R) waves. These velocities can then be well correlated to elastic moduli. Thus, UBW and USW can be described as material quality control techniques. In contrast, the IE technique is used to identify position of wave reflectors in bridge deck or pavement structures.

Thus, it is used to detect defects in the structure and can be thought of as a diagnostic tool in defect identification.

Application of UBW, USW and IE techniques in the evaluation of a bridge deck is illustrated in Figure 1. In the first part of the evaluation, the UBW and USW tests are conducted using an impact source and two receivers. The UBW technique is used to measure the velocity of propagation of compression (P) waves. By measuring the travel time of the P-wave between two receivers, the first wave arrivals, the P-wave velocity (V_P) is calculated. Because it is often difficult to identify P-wave arrivals in an automated way, a more reliable procedure to estimate the P-wave velocity is through a measurement of the surface (Rayleigh or R) wave velocity using the USW test. The USW test is identical to the SASW test *(7,8)*, except that the frequency range of interest is limited to a narrow high frequency range where the velocity of the surface wave (phase velocity) does not vary significantly with frequency *(9)*. Variation in the phase velocity would be an indication of variation of material properties (elastic moduli) with depth. Once the R-wave velocity is determined, it can be well correlated to both compression and shear (S) wave velocities, and thus to the Young's and shear moduli. In the second part of the evaluation, the IE test is conducted using an impact source and a single nearby receiver. Because of a significant contrast in rigidity of concrete and air, the elastic wave is practically entirely reflected off the bottom of the deck back to the deck surface. The frequency of the reflection, called return frequency, can be identified in the response spectrum of the recorded signal. Finally, the depth of the reflector, in this case the deck thickness, can be obtained from the return frequency and the previously determined P-wave velocity, as illustrated in Figure 1.
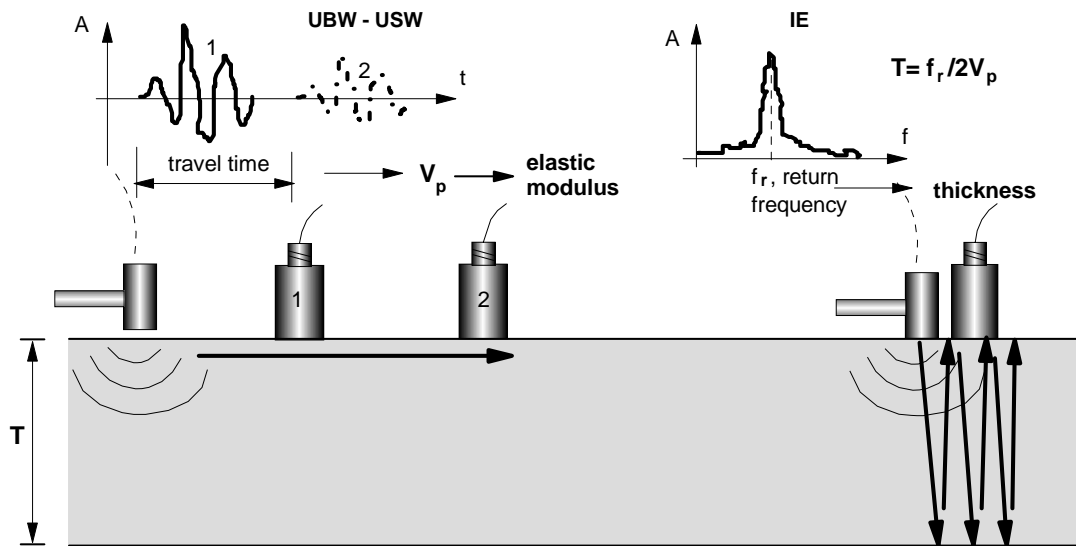
FIGURE 1 Measurement of bridge deck elastic modulus and thickness by UBW and IE methods.

While the primary objective of IE testing is to determine dominant reflectors, according to the relationship described in Figure 1, a unique thickness or depth of the reflector can be correlated to every component of the frequency spectrum. This is illustrated in Figure 2 by a frequency spectrum, and the corresponding thickness spectrum. The thickness spectrum enables simple data interpretation, because positions of the dominant and secondary peaks describe clearly the pattern of energy partitioning, and thus the degree of delamination. Spectra for a set of points along a single test line can be combined to form spectral surfaces. As shown in the same figure, frequency spectra for one test line on a bridge deck are combined to form a frequency spectral surface and are converted into a corresponding thickness spectral surface. The following observations, regarding the advantages of the two surface types, can be made when linear scales are used for both frequencies and depths. The frequency spectral surface

emphasizes presence of shallow delaminations, while the thickness spectrum emphasizes presence of apparent deep reflectors, deck zones in a serious condition that will be discussed in the following section *(10)*. Because the thickness spectral surface represents a more natural choice for data viewing, a properly selected nonlinear depth scale can provide a well-balanced image for identification of all detected reflectors.
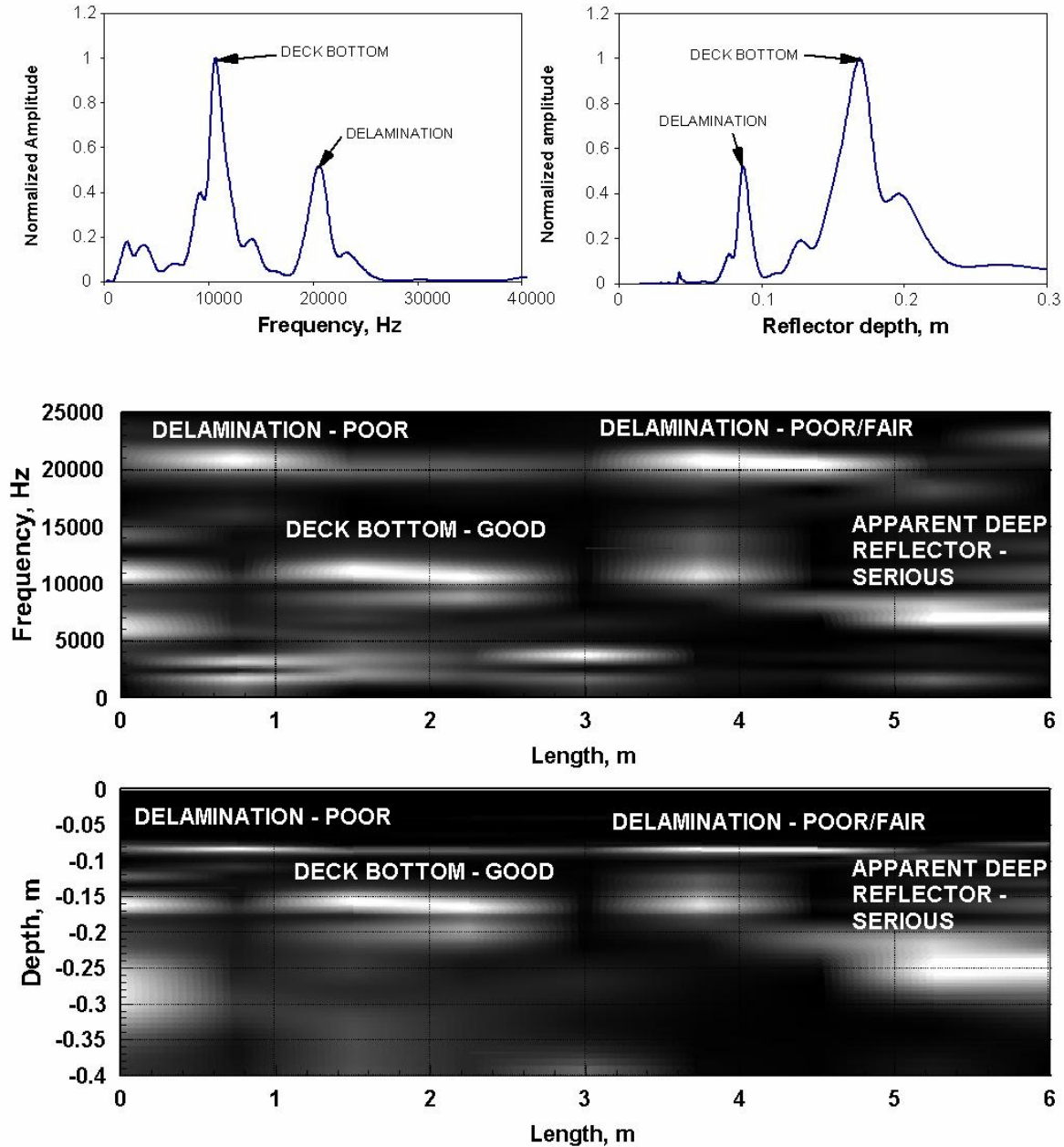
**FIGURE 2** Frequency and thickness spectra and spectral surfaces.

Current Practice of Condition Assessment

In the case of a delaminated deck, reflections of the P-wave occur at shallower depths, causing a shift in the response spectrum towards higher frequencies. Depending on the extent and continuity of the delamination, the partitioning of energy of elastic waves may vary and different grades can be assigned to

that particular section of a deck as a part of the condition assessment process. This is illustrated in Figure 3. In the case of a sound deck (good condition), a distinctive peak in the response spectrum corresponding
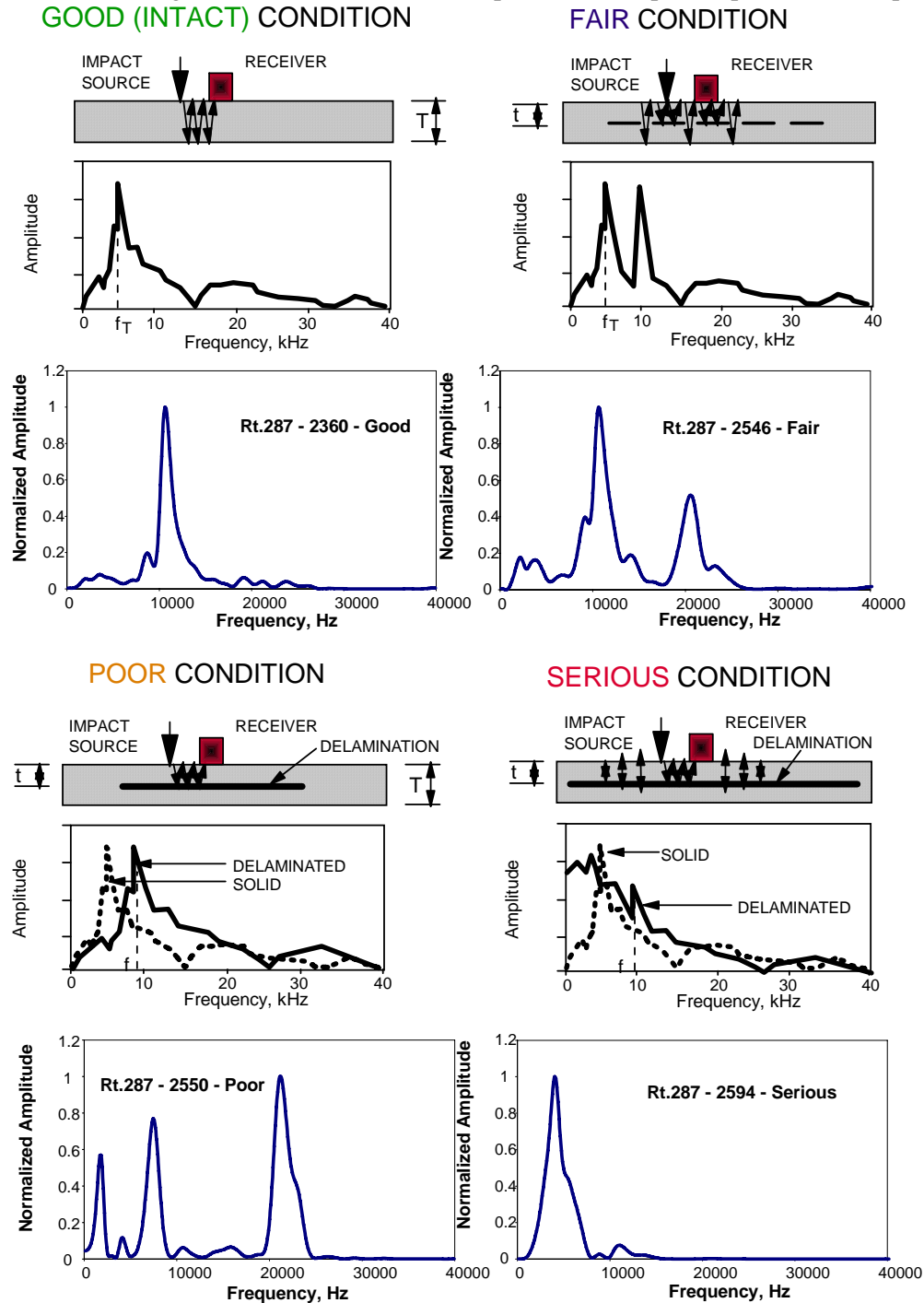
FIGURE 3 Grades for various degrees of deck delamination.

to the full depth of the deck, can be observed. This is illustrated by two spectra under the schematic of the bridge deck. The upper spectrum in the figure represents a schematic of the expected spectrum, while the lower spectrum is taken from actual field testing. Initial delamination (fair condition) is described as occasional separations between the two deck zones. It can be identified through the presence of two

distinct peaks, indicating energy partitioning from two dominant wave propagation patterns. The first peak corresponds to reflections from the bottom of the deck, while the second corresponds to reflections from the delamination. Progressed delamination (poor condition) is characterized by a single peak at a frequency corresponding to a reflector depth that is shallower than the deck thickness, indicating that little or no energy is being propagated towards the bottom of the deck. Finally, in a very severe case of a wide delamination (serious condition), the dominant response of the deck to an impact is characterized by a low frequency response of flexural mode oscillations of the upper delaminated portion of the deck. This response is almost always in the audible frequency range, unlike response of the deck in the fair and poor condition that may be in the ultrasonic range. Because it is significantly lower than the return frequency for the deck bottom, it produces an apparent reflector depth that is larger than the deck thickness.

Field Implementation of Impact Echo and Condition Maps

IE is commonly implemented in deck evaluations by conducting point testing on a grid of selected spacing. The testing is conducted using impact echo devices, which in some case integrate other ultrasonic seismic methods. One of such devices is PSPA with has a sole purpose of evaluation of surface pavement layers and bridge decks. The device integrates all three previously described ultrasonic techniques (UBW, USW, IE). The core of the PSPA system is a sensor box (Figure 4a), a box containing a solenoid type impact hammer and two high frequency accelerometers, 7.5 and 21.5 cm away from the hammer. All controls and data acquisition are in a computer that is connected by a serial cable to the sensor box. A new design of the PSPA (Figure 4c) has all data acquisition and control elements are a part of the unit. Field evaluation of bridge decks is typically done on grids of 0.6x0.6 m to 0.9x0.9 m (Figure
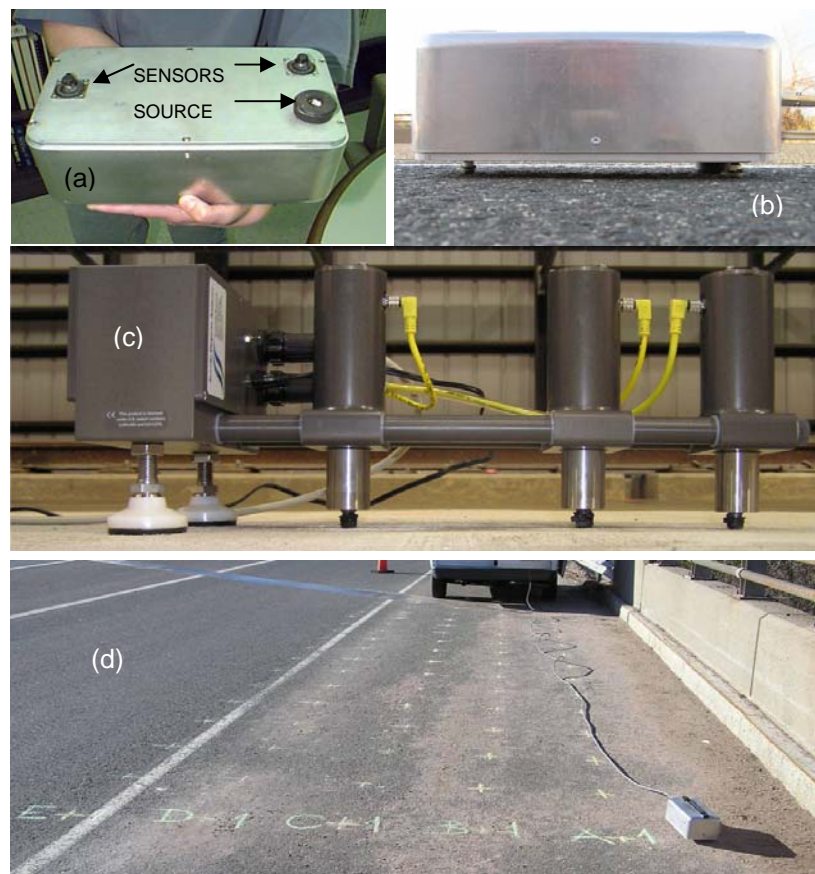
FIGURE 4 Older and newer versions of PSPA sensor box (a and c), and field implementation (b and d).

4d). Testing using the PSPA is simple and for a single point takes less than 30 seconds. The sensor box is placed at the test point (Figure 4c), a series of impacts (6-10) of 50 μs duration are applied and acceleration histories are recorded. The testing is fairly insensitive to traffic induced vibrations because of the high frequency range used—typically between 2 and 30 kHz.
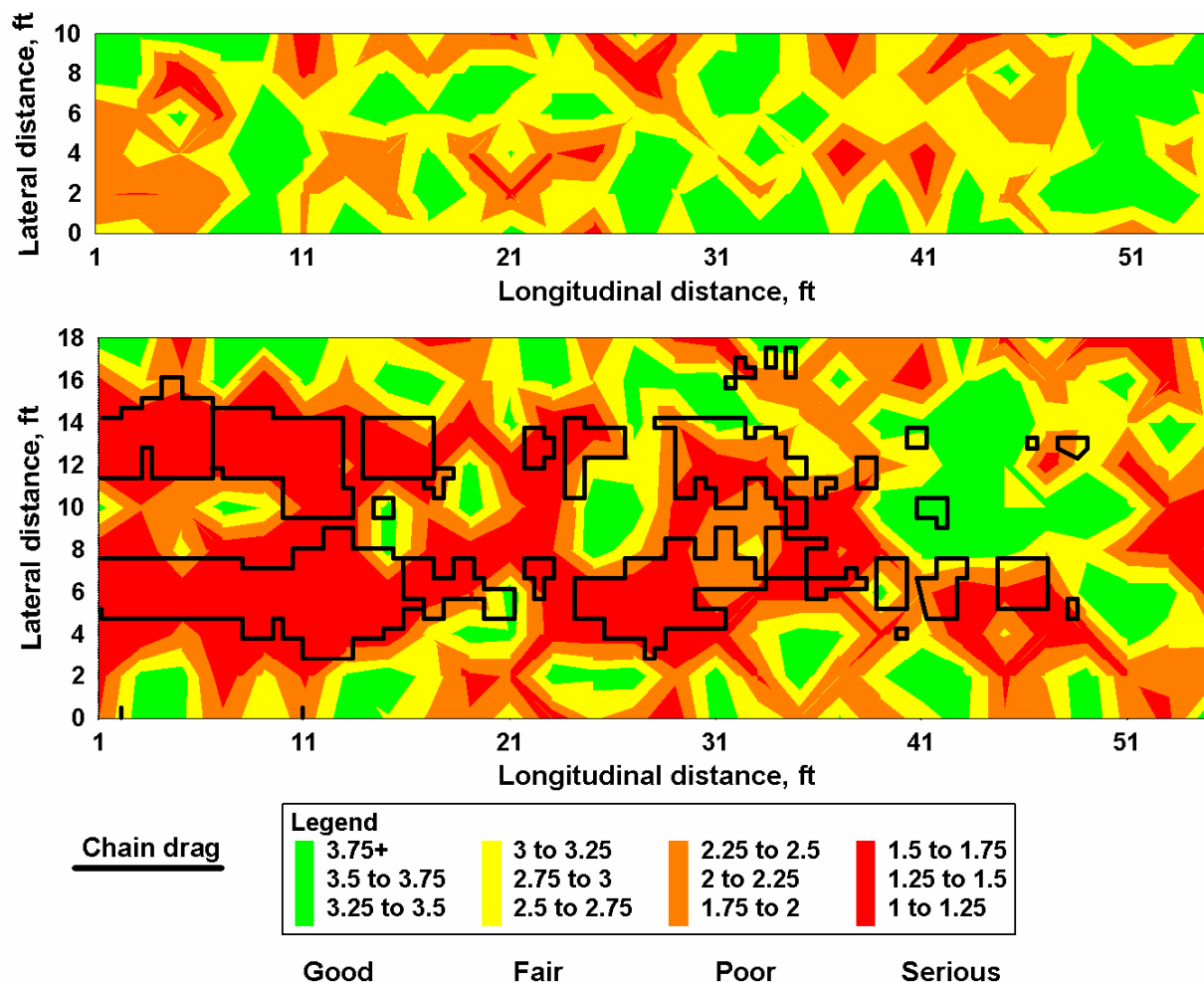

FIGURE 5 Condition assessment maps for Carter Creek Bridge (top) and Van Buren Bridge (bottom).

PSPA testing results are commonly described in terms of shear and Young's moduli (or P- and S-wave velocity) distributions, and condition assessment distributions (with respect to the degree of delamination). This is illustrated by conditions maps for sections of two bridges in Virginia, Carter Creek and Van Buren bridges (Figure 5). As can be observed in the upper condition assessment plot for the Carter Creek bridge, the deck is in a good condition and only smaller zones of initial and progressed delamination, and minor zones of a deck in a serious condition, can be identified. On the other hand, the bottom condition assessment plot for Van Buren bridge deck illustrates a deck in a significantly deteriorated condition. Zones of all previously described conditions (grades) can be identified in the condition assessment plot. Since the deck was also evaluated by chain dragging, the PSPA results were compared to those of the chain drag. The comparison points to similarity of the two approaches in detection of areas with progressed delamination (poor to serious condition). The ability of the chain drag to identify zones in a serious condition can be explained by the fact that the frequency response in such cases is in the audible range. On the other hand, the most of the zones identified by the PSPA as zones of initial delamination (fair to poor grades) were not detected by the chain drag. This ability to detect signs

of initial delamination represents a significant advantage of the PSPA device (seismic ultrasonic testing) over the chain drag approach. It allows more accurate definition of boundaries of delaminated zones, better prediction of delamination progression, and leads to better assessment and timing for implementation of rehabilitation measures.

## DATA VISUALIZATION AND INTERPRETATION

Significant enhancements in IE data interpretation can be achieved by using advanced data visualization techniques. This may include presentation of data for arbitrary vertical and horizontal cross sections in terms of spectral plots, or translucent three-dimensional plots of bridge deck sections. In all cases, the ultimate objective can be described as providing a view into the internal structure of the bridge deck and assessment of structural problems. Those may include delaminations, but IE is also suitable for detecting single or multiple scattering targets *(11)*. In the proposed bridge deck inspection framework, the IE data set is visualized in 3D space for inspection by a user.

(a)

(b)

(c)

(d)
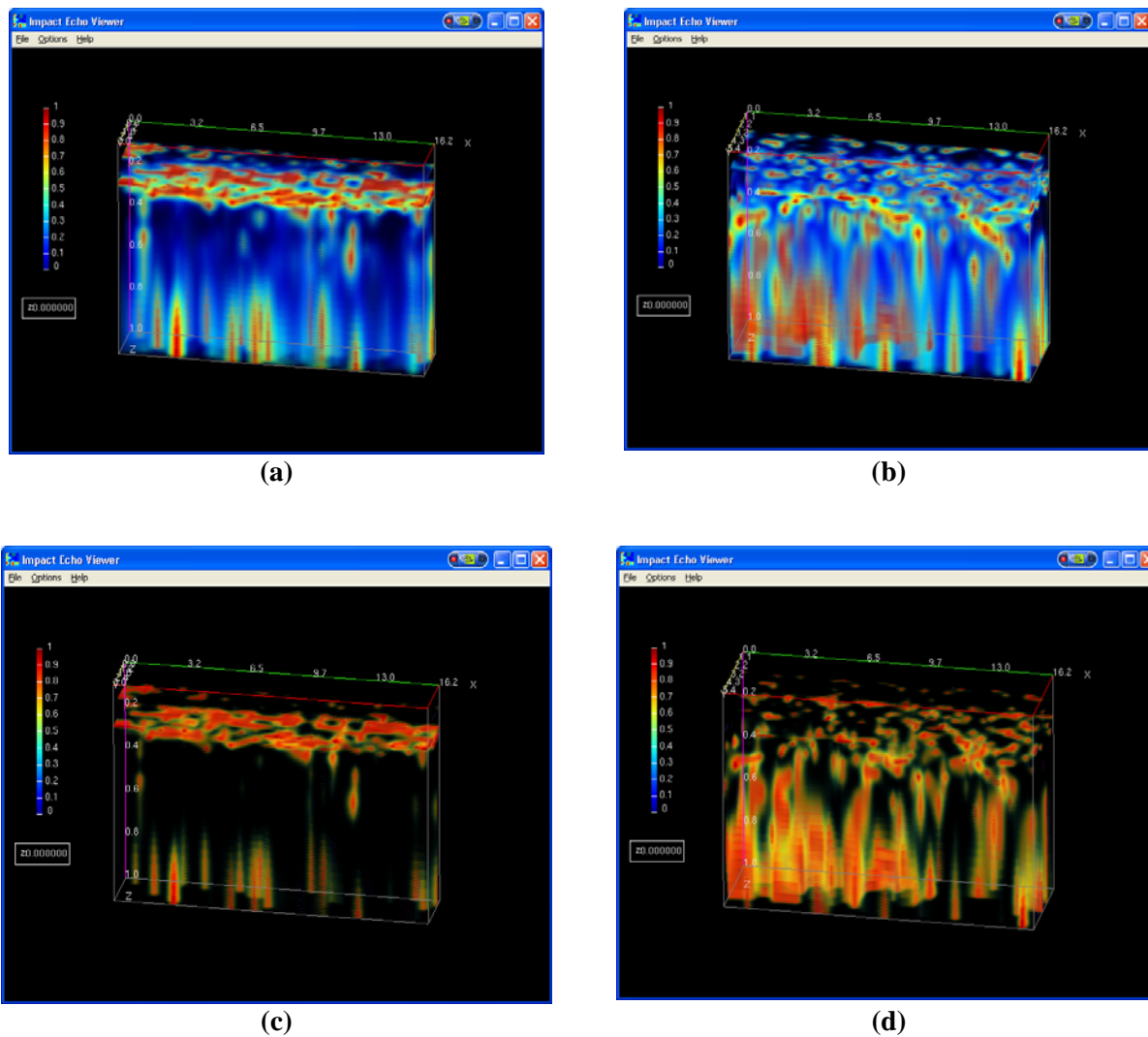
FIGURE 6 Interactive visualization of IE data. Carter Creek Bridge (a) (c), Van Buren Bridge (b) and (d).

3D Visualization of Impact Echo Data

A 3D visualization platform for IE data was developed. The platform is written in C++ for Microsoft Windows, and depicted in Figures 6a and 6b for Carter Creek and Van Buren bridge decks. The IE data consists of a reflection value, normalized in the range [0, 1], and sampled on a discrete 3D grid of voxels. Using OpenGL, the data is rendered as a series of texture-mapped planes that slice through the volume, where the reflection strength is used as an index into a colormap look-up table that consists of red, green, blue, and alpha (transparency) values. The user can rotate and shift the camera position, enlarge or shrink the volume and observe the data from different viewing positions and angles. Additionally, as shown in Figures 6c and 6d, the user can interactively adjust the transparency so that weaker reflectors become more transparent, allowing better visualization of the strong reflectors. Similar to the observations in the previous section, in the visualizations provided in Figure 6 it can be noticed that the Carter Creek Bridge, visualized in 6a and 6c is in reasonably good condition. The primary reflections are coming from the bottom of the deck. In contrast, the Van Buren Bridge, visualized in Figures 6b and 6d, has a large number of reflections throughout the volume, indicating a highly deteriorated condition. Data presented in 3D viewer can be inspected as vertical and horizontal cross sections or slices, as illustrated in Figure 7.


(a)   (b)

(c)   (d)
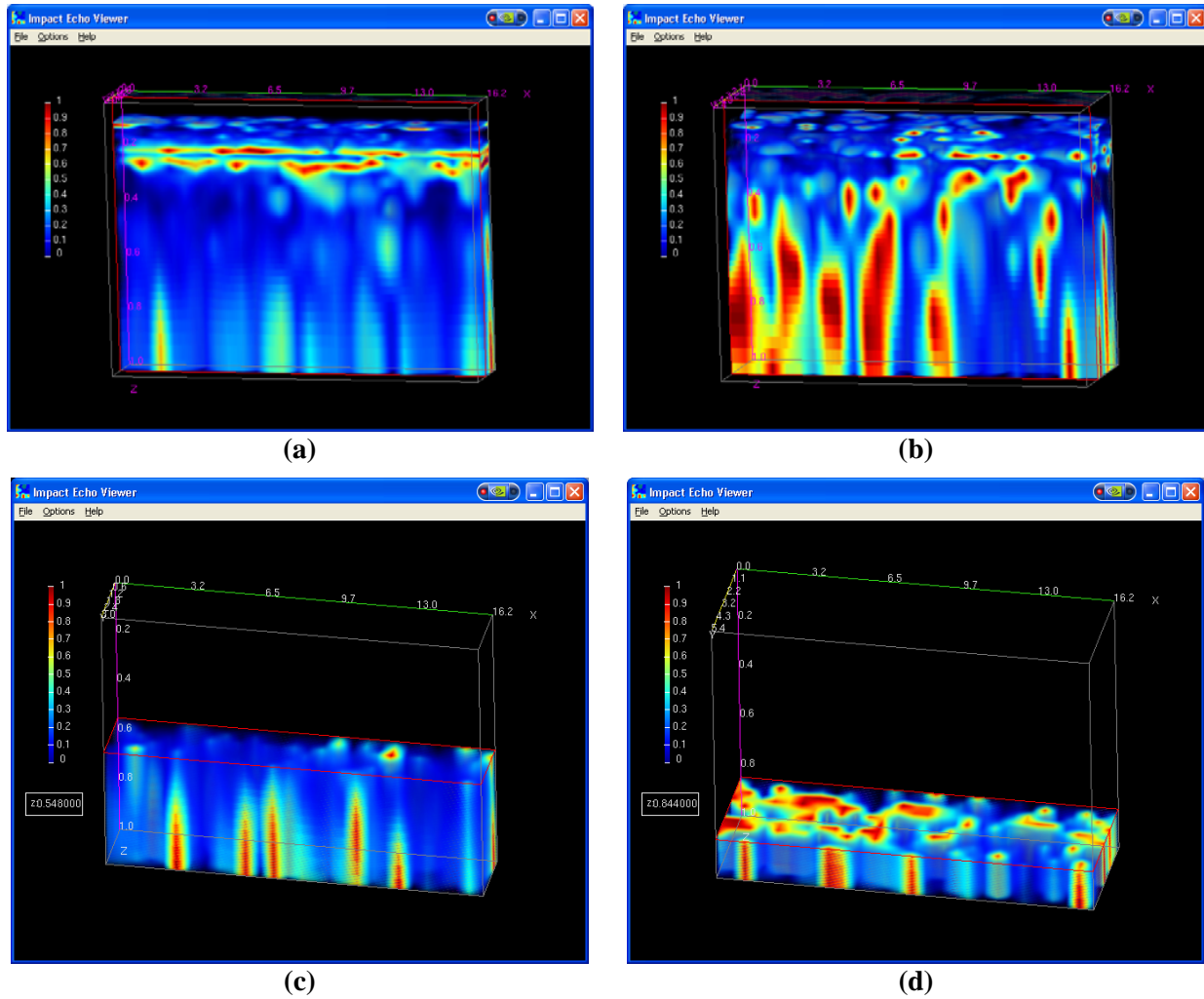
FIGURE 7 Vertical (top row) and horizontal (bottom row) cross-sections through the data. Left: Carter Creek Bridge (vertical section for y=1.6 m (a) and horizontal for z=0.54 m (c)), Right: Van Buren Bridge (vertical section for y=3.5 m (b) and horizontal for z=0.84 m (d)).

Data Analysis and Interpretation

While data visualization is very useful for the user to visually inspect the bridge deck data, this framework also provides analytical software tools that characterize the IE data and provide the *overall assessment of the condition of a bridge deck*. The same tools are used to identify zones of the deck that require repair or rehabilitation. The sections below describe these tools that are based on the distribution of reflection intensity. While a number of bridge decks were analyzed, results for Carter Creek and Van Buren bridge decks are presented herein to highlight the application of these analytical software tools.

Reflection Intensity vs. Depth Relationship

To locate the depth of the strongest reflectors, which could be indicators of defects in a bridge deck, it is very useful to study the relationship between the reflection intensity and depth of the bridge deck. In Figure 8a, strongest reflections appear around a depth equal to about 0.2 m, which corresponds to the bottom of the deck. This phenomenon indicates that the deck is in good condition, consistent with the previous observation and analysis. However, in Figure 8b, strong reflections appear throughout the deck, particularly in the lower regions (close to a 1 m depth) of the deck, indicating presence of flexural oscillations of the upper portion of the deck and thus serious condition.


(a)   **(b)**
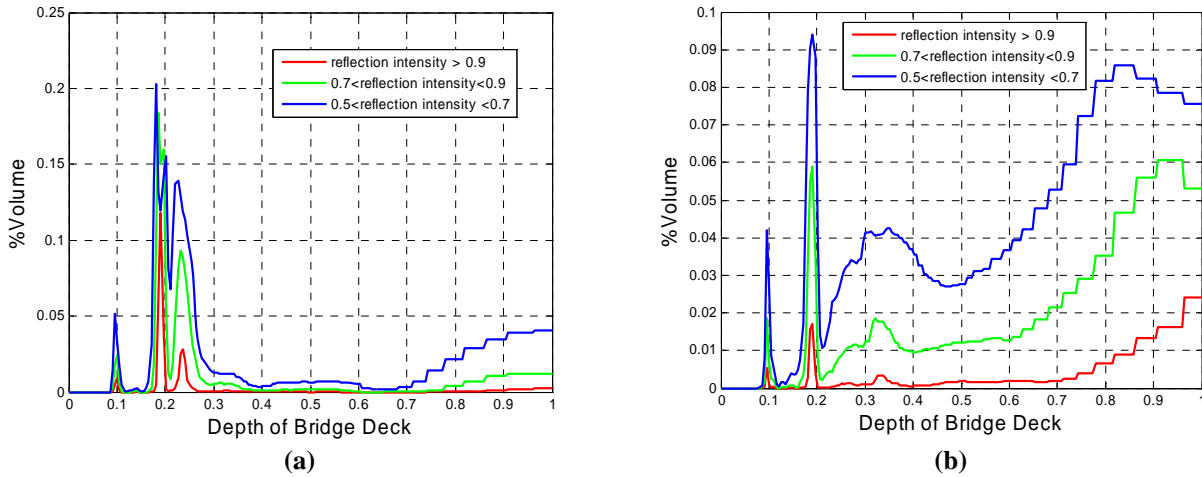
FIGURE 8 Percent Volume for Various Reflection Intensities vs. Depth. Carter Creek (a), Van Buren (b).

Cumulative Distribution of Reflection Intensity

We also examined the cumulative distribution of reflection intensities, shown as Fig. 9. Specifically, these graphs plot the percentage of the IE reflectivity that is greater than or equal to a specific reflection strength. From this figure, it is obvious that strong reflectors at depths deeper than the bottom of the deck are existing in the Van Buren (b) are more than those in the Carter Creek Bridge (a). This is considered to be a sign that the former bridge deck is in a worse condition. Quantitatively, this can be presented in terms of the areas under the curve, which for Carter Creek is 1909.8 and Van Buren Bridge 2376.6.
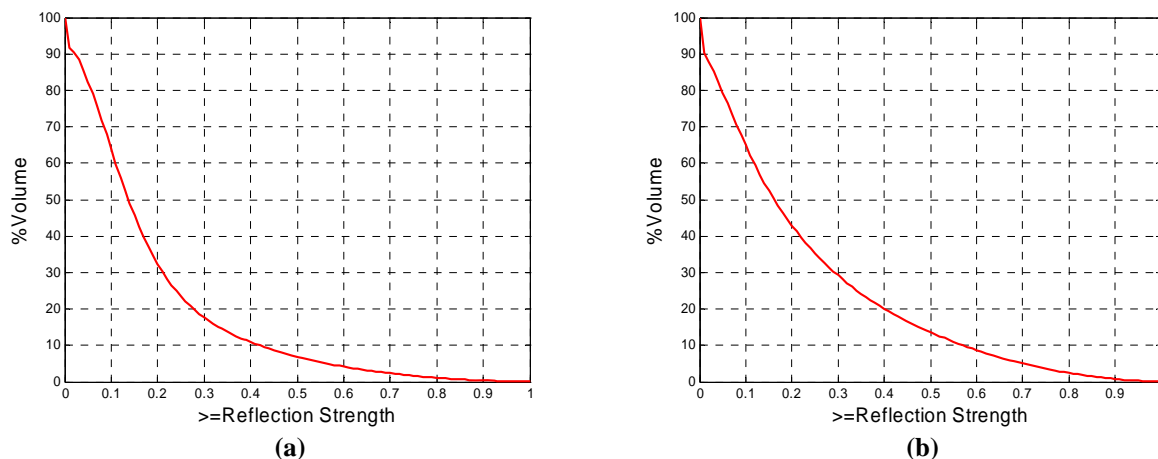
FIGURE 9 Cumulative Distribution of Reflection Intensity. Carter Creek Bridge (a) and Van Buren Bridge (b).

Histogram of All Reflection Intensities

A histogram is the graphical version of a table which shows what proportion of cases fall into each of several or many specified categories. In Fig. 10, the histograms of both bridges are shown. It is worthy noting that the percentage of volume of strong reflection intensity in Carter Creek Bridge is less than Van Buren Bridge, which supports the previous analysis that the latter one is more deteriorated.
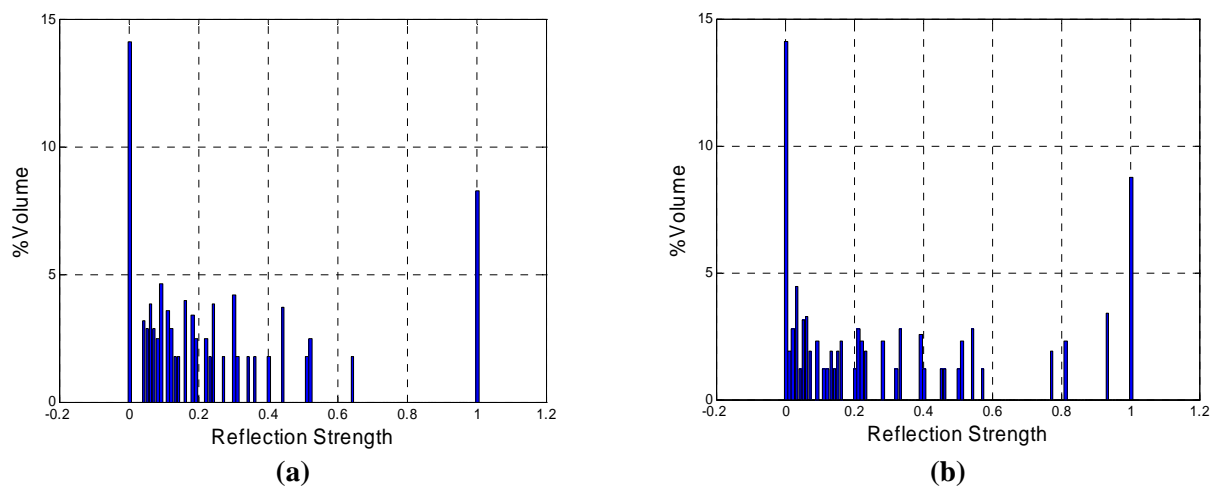
FIGURE 10 Histogram of Reflection Intensity. Carter Creek Bridge (a), Van Buren Bridge (b). Log(%volume(at each reflection strength)) + constant.

Identification of Repair Areas

From the practical point, of highest interest and benefit is identification of zones on the deck that are in serious condition (progressed delamination) or fair to poor condition (initial delamination). The process of identification of such zones is illustrated in Figure 11. Initial delamination (fair to poor conditions) is primarily identified by medium to strong reflections at the depth corresponding to the position of the top rebars. This is illustrated in Figures 11a and 11e for Carter Creek and Van Buren bridges, respectively,

with strong reflection maps for slices between 7 and 13 cm. Similarly, sound zones of the deck are identified by strong reflections from the bottom of the deck, or in this case described by slices between 16 and 24 cm depth in Figures 11b and 11f. (Clearly, the Carter Creek Bridge deck is in a better condition.) Finally, progressed delamination (serious condition) can be described by strong reflection maps for the slice for the depth deeper than the depth of the bottom of the deck. This is illustrated by the strong reflection maps for slices between 30 cm and 1 m in Figures 11c and 11g. To obtain the map of zones candidates for repair, the map for serious condition is superimposed on the map of initial delamination, as e.g. repair map in Figure 11d is obtained from the map in Figures 11c superimposed on the map in Figure 11a. A comparison of maps for Carter Creek Bridge in Figure 11d and Van Buren Bridge in Figure 11h points clearly to significantly higher deterioration and need for repair of the latter one.

SUMMARY AND CONCLUSIONS

Ultrasonic seismic tests, and IE in particular, can be successfully used in evaluation and long term monitoring of concrete bridge decks. The monitoring can encompass changes in both material characteristics (primarily elastic moduli), and the deck condition with respect to deterioration caused by corrosion induced delamination. In contrast to the chain drag practice, the condition assessment with respect to delamination by ultrasonic methods allows detection of zones of delamination at various stages, from initial to progressed and developed.

Advanced data visualization techniques can significantly improve the accuracy and ease of data interpretation. Application of a three-dimensional translucent imaging to IE testing results enables an impact echo device to be used as a kind of a bridge deck sonar device. The presented visualization and interpretation algorithm platform allows both the overall assessment of the condition of the deck and identification of deteriorated zones of the deck for repair or rehabilitation in an efficient and intuitive way.

(a)　　　　　　　　　(b)　　　　　　　　　(c)　　　　　　　　　(d)

(e)   **(f)**   **(g)**   **(h)**
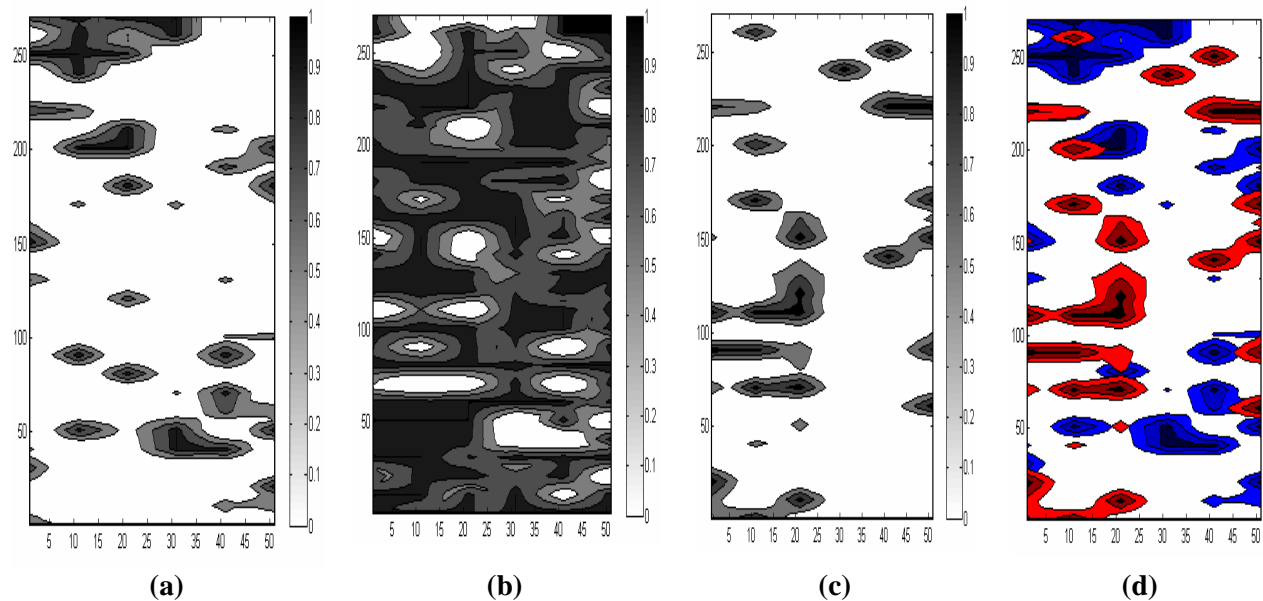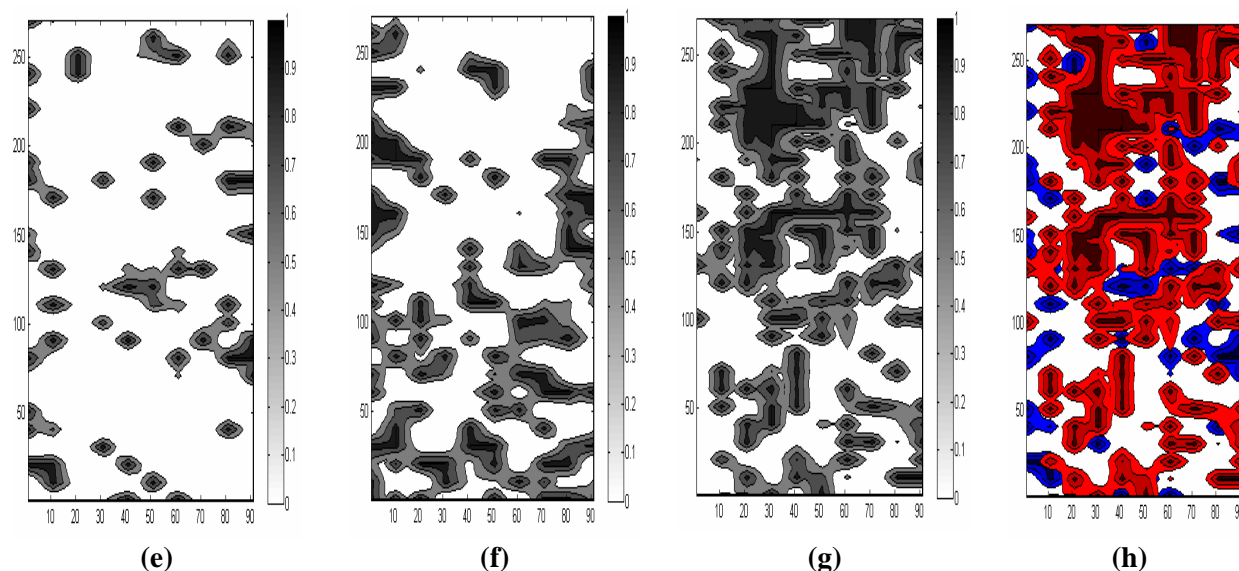
FIGURE 11 Plan view contour plots for deck repair.   Top: Carter Creek Bridge, Bottom: Van Buren Bridge. Left to right: the maximum reflectance in the "delamination zone" slice (0.07m~0.13m) (a)(e), in the "bottom of the deck" slice (0.16m~0.24m)(b)(f), and in the "apparent deep reflector" zone (0.3m~1m)(c)(g). Identified deteriorated zones (d) and (h) (red - serious condition, blue – fair to poor condition).

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