# TOMOGRAPHIC IMAGING OF CONCRETE STRUCTURES CONTAINING PLANNED DEFECTS

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**Abstract**

Results from two-dimensional (2-D) and three-dimensional (3-D) tomographic imaging investigation on a concrete wall and a drilled shaft foundation containing engineered defects are presented. Both concrete structures contained four water-filled steel access tubes. Each pair of access tubes provided one vertical survey panel for a total of six panels. The datasets obtained from each panel, or combination of panels, were then used to construct 2-D and 3-D tomographic images. Both standard zero-offset as well as the multi-offset crosshole sonic logging (CSL) datasets were acquired.

Based on the results obtained from the Blackhawk's tomographic imaging system (CSLT-3D™) and standard CSL, the research study was successful in detecting defects and determining the following:

- 2-D and 3-D tomographic imaging of the standard *zero-offset* CSL data provides an enhanced visualization of the results over the standard CSL 1-D log display format.
- *Multi-offset* tomography provides a better image of the defects than standard CSL and the percentage drops in velocity were more accurately assessed (defect characterization). Standard CSL underestimated the percentage drop in defect velocity. Therefore, the relationship between velocity and strength is inaccurately assessed by the standard CSL.
- Multi-offset tomographic imaging provides an accurate spatial definition of the defects for confirmation through coring.

The CSLT-3D™ tomographic technology enhances visualization of the structure's interior and provides greater detail of defects for confirmation through coring, and defects are easier to characterize.

Three main benefits of tomographic imaging are identified over standard CSL for detecting defects and voids in concrete foundations:

1. Tomographic imaging provides better spatial resolution of defects for confirmation through coring followed by remedial action (if necessary);
2. Tomographic (velocity) images provides a more accurate correlation between percentage drop in velocity with percentage drop in concrete strength for shaft acceptance criteria; and,
3. 2-D and 3-D tomography, when performed routinely, will provide engineers in the owner agencies a tool for assessing the integrity of drilled shaft foundations without further costly delays to construction.

## 1.0 Introduction

The results obtained from the crosshole sonic logging tomographic (CSLT) survey and the standard crosshole sonic logging (CSL) conducted on a test wall and a drilled shaft foundation containing engineered defects are presented herein. The objective of these investigations were to demonstrate the effectiveness of Blackhawk's CSLT-3D$^{TM}$ two-dimensional (2-D) and three-dimensional (3-D) tomographic imaging system in detecting defects, their sizes, and their lateral extent in concrete structures. Both standard zero-offset as well as the multi-offset crosshole sonic logging (CSL) dataset were acquired.

## 2.0 Test Geometries

The test wall (Figure 1) was 2.1 m long (6.9 ft) by 0.6 m wide (2 ft) by 2 m high (6.6 ft) and was constructed by Foundation Techniques, Ltd. of Hong Kong.

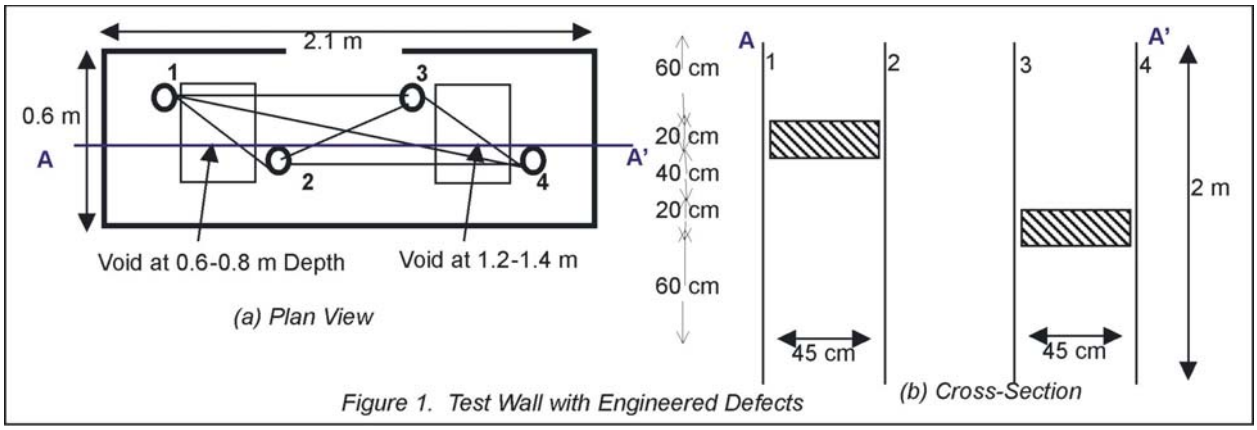


*Figure 1. Test Wall with Engineered Defects*

The drilled shaft (Figure 2) was 1.2 m (4 ft) in diameter and 15.2 m (50 ft) in length and was constructed at the National Geotechnical Experimental Site (NGES) research site, Amherst, MA.

The wall and the shaft concrete structures contained four (4) water-filled access tubes and each pair of access tubes provided one vertical survey panel for a total of six panels. The datasets obtained from each panel, or combination of panels, were then used to construct 2-D and 3-D tomographic images for further analysis and interpretation.

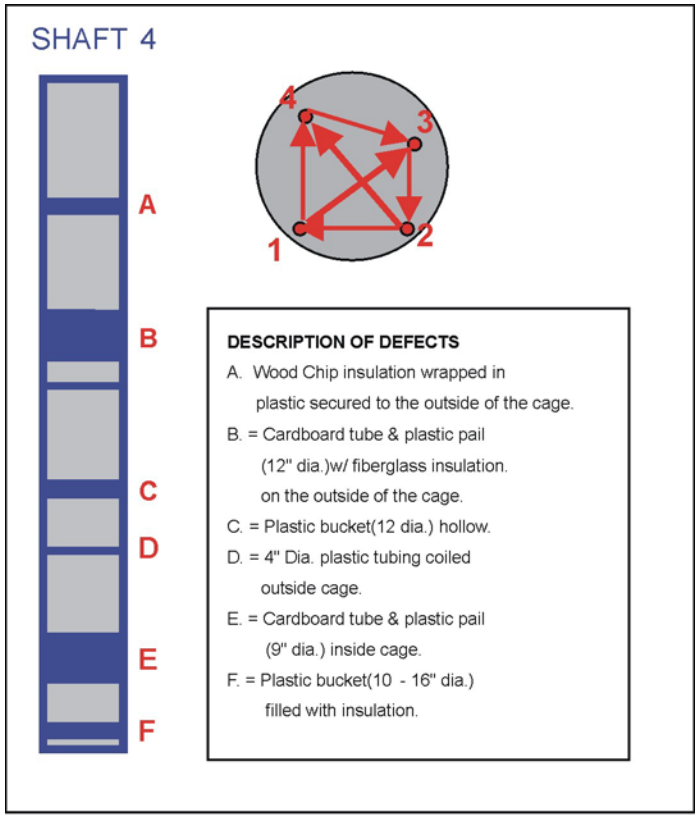


*Figure 2. Drilled Shaft with Engineered Defects*

## 3.0 Data Acquisition Procedures for CSL and CSLT

**3.1 CSL Method.** In the standard CSL method (Figure 3), ultrasonic transmitter/receiver probes are initially lowered to the bottom of a pair of access tubes. The two probes are then pulled simultaneously as to maintain near horizontal ray paths between them (*zero-offset logging*). The system is calibrated to

measure the sonic wavefield at 5 cm (2.4 in) depth intervals throughout the length of the shaft. This test is repeated for all test paths along the outer perimeter as well as across the inner diagonal of the shaft. Good concrete condition will result in a near continuous vertical alignment of the waterfall-displayed data (and travel time picks). Longer travel times and lower signal amplitudes characterize anomalous zones, defined as defects, due to soil intrusions, voids, or poor quality concrete.

CSL data can also be collected by initially offsetting either the source or the receiver and then pulling the two probes together as to maintain a constant non-zero angle between them (*Offset Logging*).

**3.2 CSLT Method (Offset Tomography).** In the CSLT method (Figures 4 and 5), data is collected by running a zero-offset log in combination with several positive offset (receiver is shallower) and negative offset (source is shallower) logs. This procedure is repeated for all possible access tube combinations to form a three-dimensional tomography dataset.

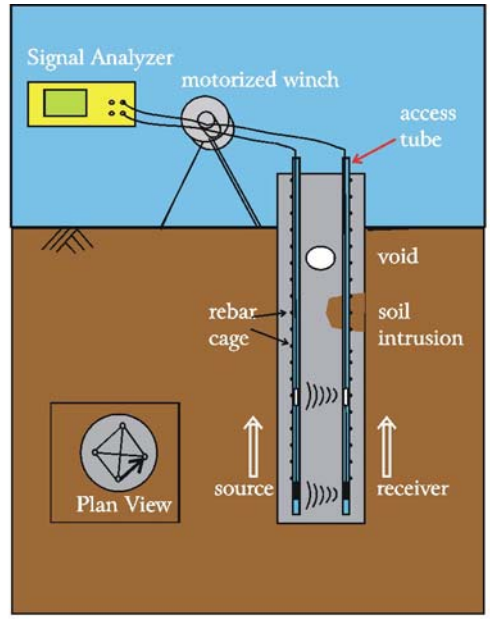


*Figure 3. Crosshole Sonic Logging (CSL) Field Setup*

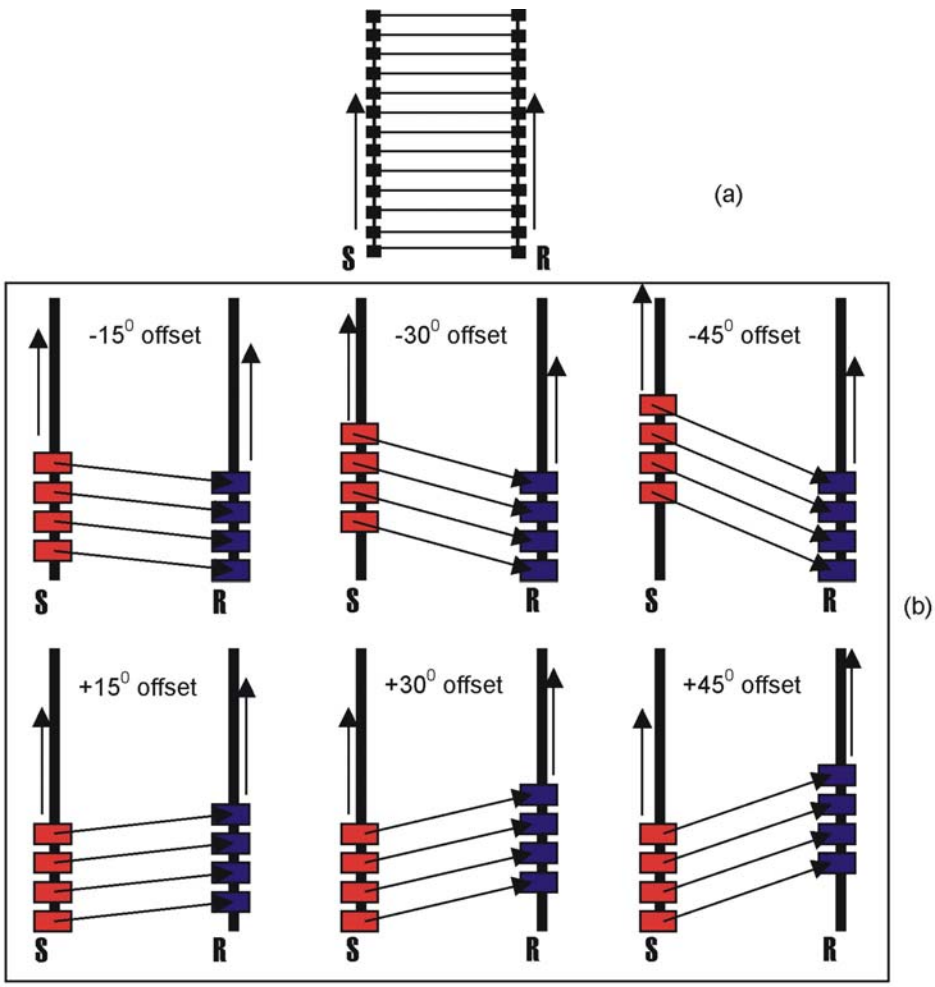


*Figure 4. Zero-Offset CSL Versus Multi-Offset Tomographic Data Collection Procedure (a) Zero-Offset (b) Three Negative Offsets (Source is Up) and Three Positive Offset (Receiver is Up)*

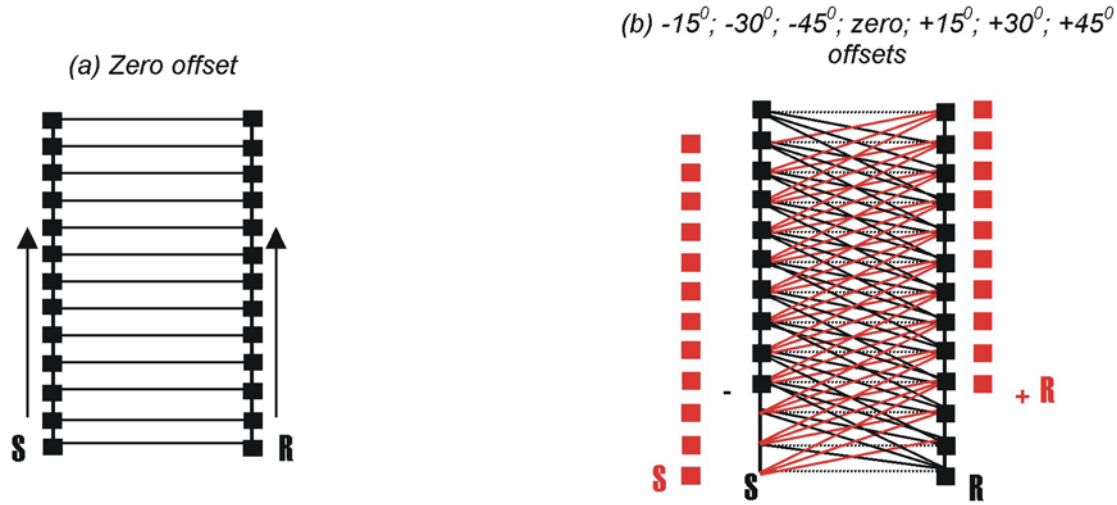


*Figure 5. a) Ray-Density with Zero-Offset Data Collection*
*b) Tomographic Data Collection (Zero Plus Three Positive and Three Negative Offsets)*

## 4.0 CSL and Offset Logging 1-D Data Presentation Formats

Figure 6 presents standard CSL logs (in waterfall display format) acquired between all six (6) test panels on the test wall compared side by side. In these figures, a full-waveform gray-scale vertical stack of the data traces is displayed as a function of depth in the right hand track. In the left hand track, the picked travel time arrivals (thin line) and signal amplitude (thick line) are also displayed. For each trace, the root mean squared (RMS) amplitude level is calculated within a 300-microsecond window starting from the picked travel time. Each plot presents the raw CSL field data (no filtering or zero muting applied) from one combination of access tubes as indicated on the bottom of each log.

A typical offset log combination set for the test wall panel 1-2 is shown in Figure 7. Please note that the travel time anomalies become broader as offsets are increased. Note that for offsets approaching 45º, a full symmetrical travel time log could not be realized due to the wall's height limitation.

### 4.1 Defect Definition

Using standard CSL or CSLT-3D™ testing, "questionable" concrete condition is defined as a zone with a decrease (from median) in sonic velocity between 10% and 20% (or about 40%-65% of old strength); and, "poor" concrete condition is defined as a zone with greater than 20% decrease in sonic velocity (or about less than 40% of old strength)[1].

## 5.0 Interpretation of CSL Results from the Test Wall

As shown in Figure 6, only two travel time anomalies are observed in the CSL data between test panels 1-2 and 3-4. For the test panels 1-3 and 2-4, the geometry was such that the fastest (first) wave arrivals clearly went around the defects without a significant change in apparent velocity. Therefore, in this tube geometry, the panels 1-3 and 2-4 do not contribute significantly to the tomographic imaging; so most of the recovered information is from 2-D imaging between panels 1-2 and 3-4. Moreover, the velocity anomaly for test panel 1-4 is less than 10%; and, thus it would not be reported as a defect.

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[1] U.S. Federal Highway Administration (FHWA) Section 565 (1996) Specification for drilled shafts (construction requirement)—integrity testing. Please note that the correlation between velocity and concrete strength is from empirical relationships. Blackhawk is currently involved in a research study with FHWA to statistically define a defect cut-off velocity and empirically compute the relationship between velocity and strength for the same concrete mix used in the construction of the shaft.

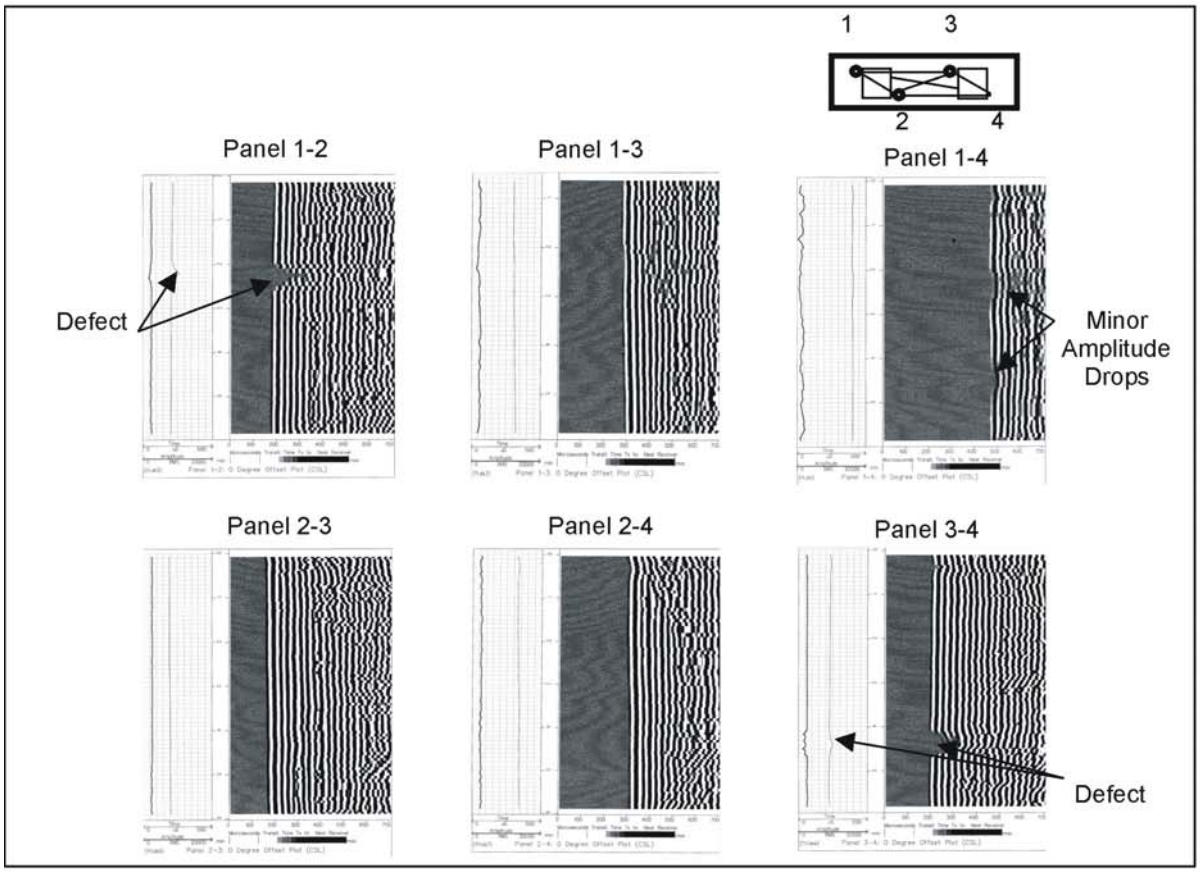



*Figure 6. Test Wall - Zero-Offset CSL Dataset For All Test Paths*

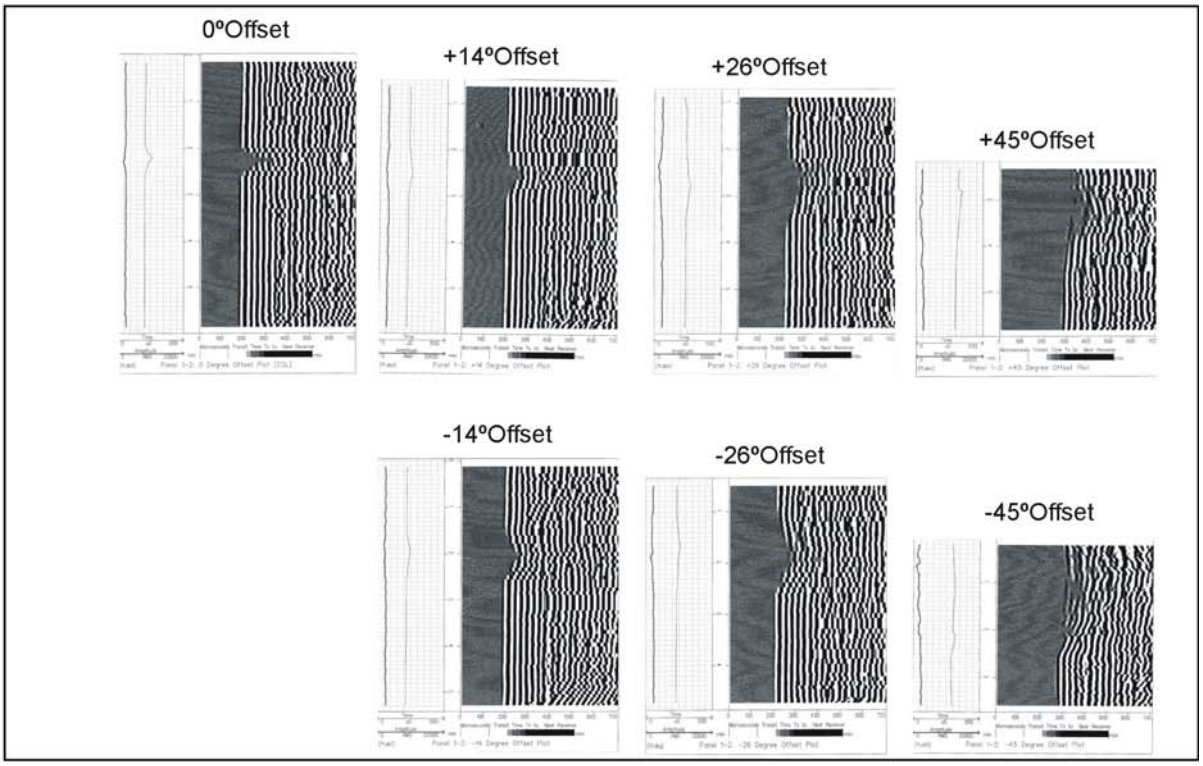



*Figure 7.* Test Wall - *Multi-Offset Log Combination For the Test Panel 1-2*

## 6.0 Tomographic Inversion and Imaging

In the tomographic inversion technique, a set of predicted travel times is obtained by wavefield extrapolation, or ray tracing, through a presumed theoretical model (forward modeling). The travel time equations are then inverted iteratively in order to reduce the root mean square (RMS) error between the observed and computed travel times. The inversion results can be used for imaging the velocity (travel time tomography) and attenuation (amplitude tomography) distribution between access tubes.

As noted earlier, data were acquired in both the zero-offset (standard CSL) and multi-offset methods. Tomographic imaging was performed using both 2-D and 3-D algorithms. **Therefore, four combinations of tomographic images can be obtained.**

2-D and 3-D tomographic imaging can be performed using zero-offset data for enhanced visualization of data over standard 1-D CSL logs. However, for proper imaging and (velocity) characterization of defects, multi-offset CSL data should be acquired.

### 6.1 Zero-Offset Versus Multi-Offset 2-D Tomographic Imaging – Test Wall

The results of two-dimensional (2-D) tomographic imaging for the Panels 1-2 and 3-4 are shown in Figures 8a and 8b, respectively. In these figures, standard zero-offset CSL tomographic images on the left are compared with the multi-offset tomographic images on the right. The zero-offset images showing defects that are horizontally elongated due to the limited (practically zero) vertical ray coverage of the standard CSL method and they exhibit a more limited distribution of color (velocity range). Moreover, velocity values tend to be averaged out and distributed horizontally. Therefore, fractional changes in velocity obtained by the standard zero-offset CSL logs are generally inaccurate.

For example, in Figure 8a, the zero-offset image at 70 cm (2.3 ft) indicates a 17% drop in velocity (questionable concrete) whereas the multi-offset image indicates a 26% drop in velocity (poor concrete). In Figure 8b, the zero-offset image at 130 cm (4.3 ft) indicates a 10% drop in velocity (acceptable-questionable) while the multi-offset image indicates an 18% drop in velocity (questionable-poor). The clarity of the defects detected between these two tube pairs is much better defined in both of the multi-offset datasets. Definition of the defect size and location cannot be discerned from the zero-offset tomographic imaging.

### 6.2 Zero-Offset Versus Multi-Offset 3-D Tomographic Imaging – Test Wall

Offset logs for all 6 panels and 7 offsets (i.e., 42 logs) were combined and input to the three-dimensional tomographic imaging module with results shown in Figure 9. In this figure, at the top left hand side (Figure 9a), a 2-D plan view and the cross-sections of the wall indicates the shallower defect at a depth of about 70 cm (2.3 ft) in, and the deeper defect (Figure 9b) at a depth of about 130 cm (4.3 ft). Again, note the distortion for the geometry of the rectangular wall in the plan view plots.

3-D Cross-sectional views comparing zero-offset versus multi-offset tomography are shown side by side for comparison for the respective panels. Once more, note the better images defined by the 3-D multi-offset tomographic inversion versus standard zero-offset CSL (especially between panels 1-2 and 3-4) and the greater velocity distribution range. Also, tomographic images indicate a secondary (unplanned) defect located between Tubes 1-3 near the bottom of the wall.

The vertical streaking in the 3-D image is due to the few crossing of rays in the plan view; i.e., the number and distribution of tubes are insufficient for 3-D imaging. Also, as previously noted, the tube geometry was such that the ray paths grazed the targets in Panels 1-3 and 2-4; and, therefore, they could not be fully imaged in 2-D or 3-D CSL or CSLT.

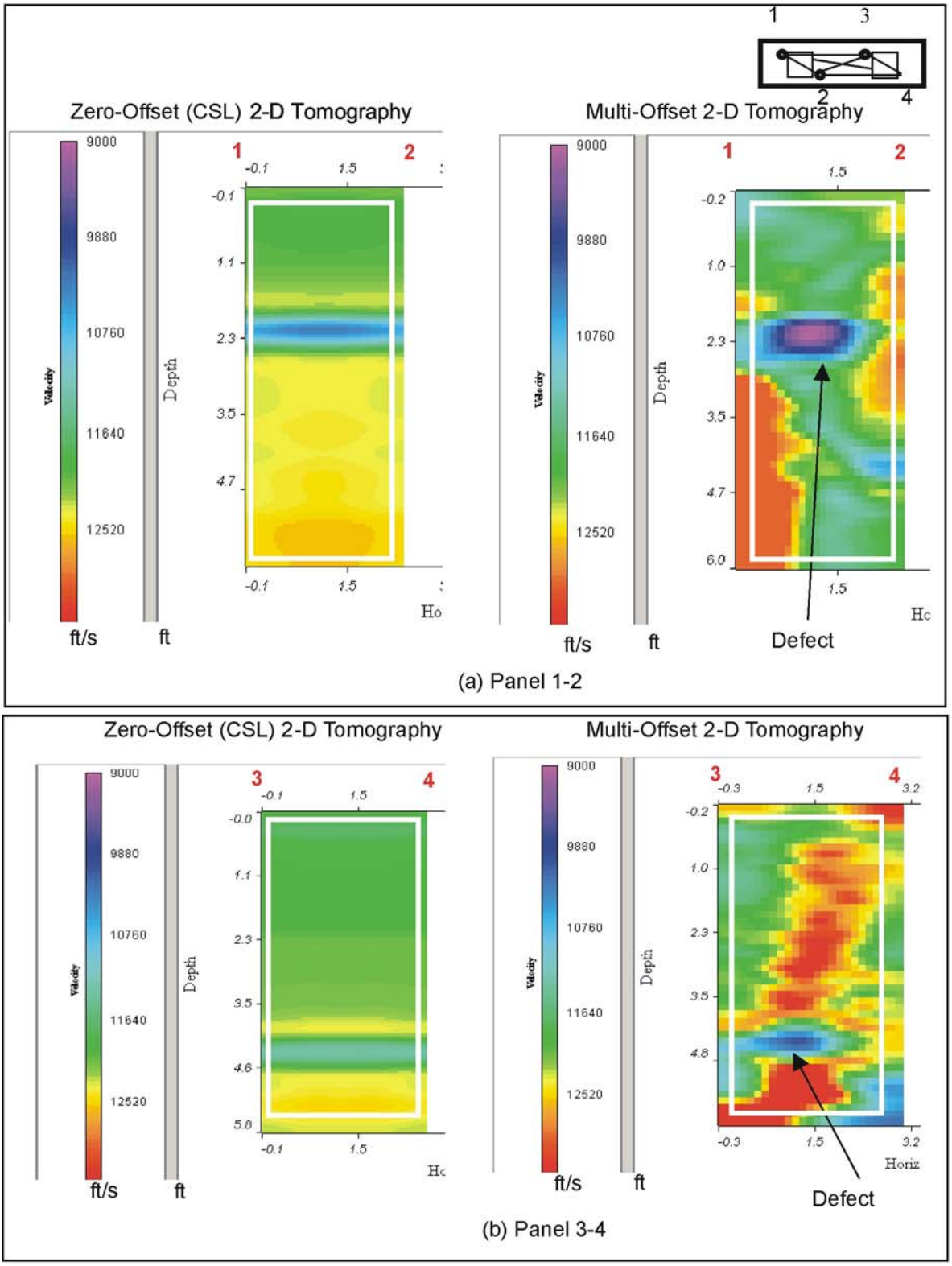
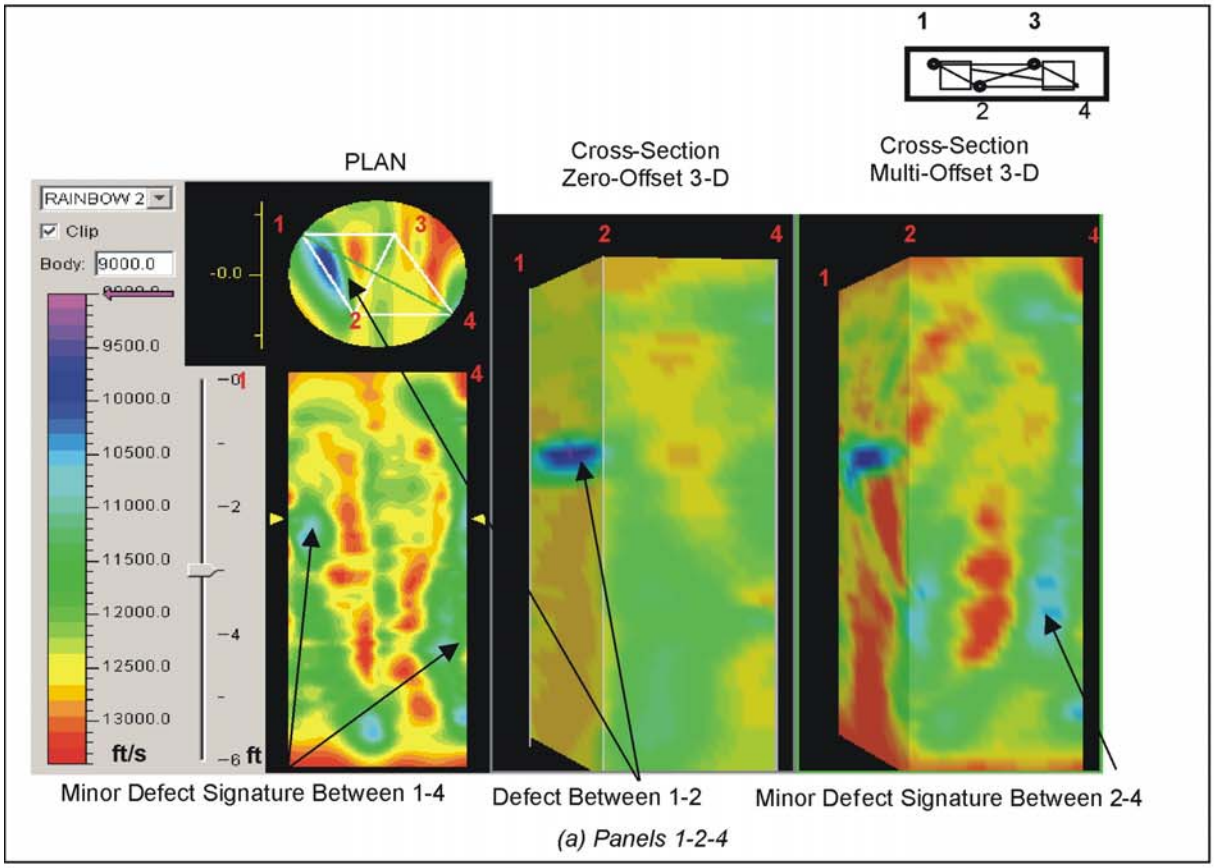
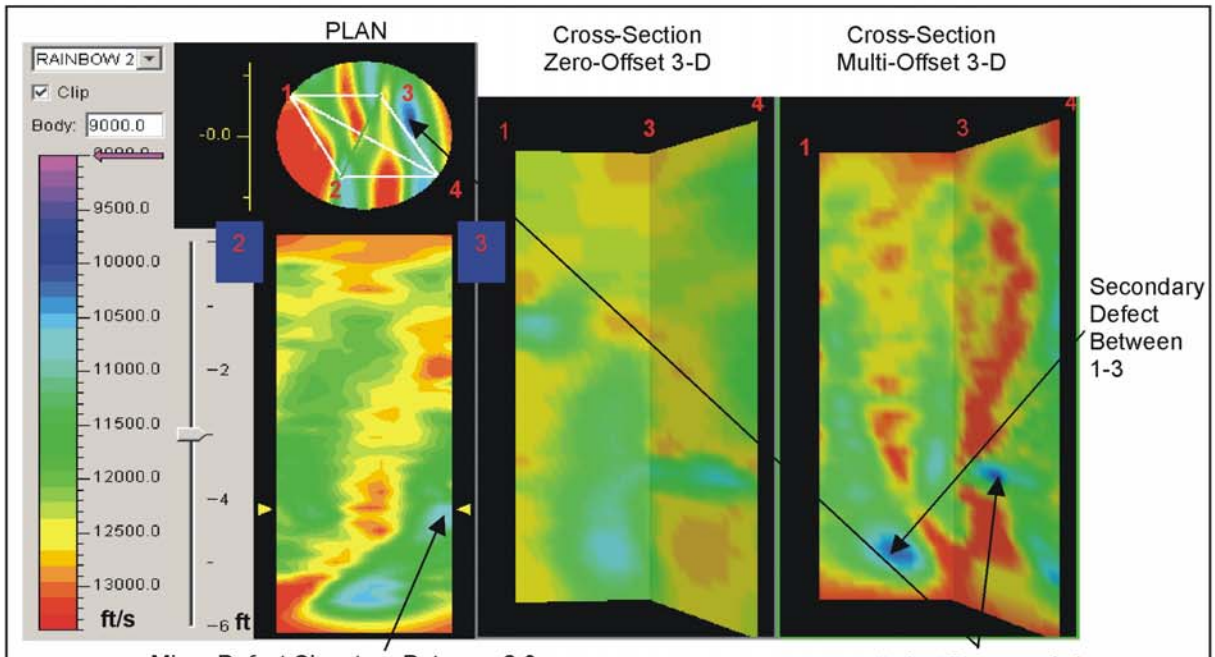



*Figure 8. Comparison between Two-Dimensional Zero-Offset (CSL) Tomography (Left) and Multi-offset Tomography (Right) for Panel 1-2 and Panel 3-4*




*(a) Panels 1-2-4*




*(b) Panels 1-3-4*

*Figure 9. Comparison Between Zero-Offset (CSL) and Multi-Offset 3-D Tomography in the Test Wall. Panels 1-2-4 are shown in (a) and Panels 1-3-4 are shown in (b)*

The final interpretational results from the test wall can be summarized as follows:

1. Standard zero-offset CSL data logs *detected* the two planned defects in 2 out of 6 test panels (Panels1-2 and 3-4).
2. 2-D and 3-D tomographic imaging of the zero-offset CSL data also detected the planned defects in 2 out of 6 panels (Panels1-2 and 3-4), with partial indication in Panel 1-4. Due to the tube geometry and grazing of rays around the defects, limited detection was observed between Panels 1-3 and 2-4. No defect was observed between Panel 2-3, as expected.
3. 2-D and 3-D imaging of multi-offset data *imaged* the planned defects in 2 out of 6 panels (Panels1-2 and 3-4) with partial indication in panel 1-4 as well as and additional unplanned defect between 1-3 with a 16% drop in velocity. Again the tube geometry was such that the ray paths grazed the targets in Panels 1-3 and 2-4; and, therefore, they could not be fully imaged in 2-D or 3-D. No defect was imaged between Panel 2-3, as expected.

### 6.3 Zero-Offset and Multi-Offset 3-D Tomographic Imaging – Drilled Shaft 4 at NGES

The data were acquired and processed by Blackhawk GeoServices under contract with Central Federal Lands Highway Division (CFLHD) in order to evaluate the integrity of drilled Shafts 1 and 4 at the National Geotechnical Experimentation Site (NGES), Amherst, MA. The following objectives were addressed:

- Evaluate the accuracy of the CSL method for detecting known defects in deep-foundation concrete structures utilizing zero-offset tomographic imaging.
- Evaluate the accuracy of the CSL method for detecting known defects the same structures when utilizing multiple-offset tomographic imaging.

For the Drilled Shaft 4 at NGES, offset logs for all 6 panels and 7 offsets (42 logs) were combined and input to the three-dimensional tomographic imaging module. Data presented in Figure 10 are only from Shaft 4 using CSL and CSLT 3-D imaging. Primarily, the interpretations are based on identifying low velocity zones that have velocities less than 15% of the average concrete velocity in Shaft 4 ($V_{ave}$= 4000 m/s). Low velocity zones were also identified that have less then a 10% reduction from the average velocity.

The final interpretational results from Shaft 4 (Figure 10) can be summarized as follows:

1. Standard CSL testing resulted in detection of 3 low velocity zones out of 7. These 3 zones have reductions in velocity of more than 15%, but one low velocity zone with only a 5% reduction from the average velocity was detected within the shaft.
2. Using the CSLT technique resulted is detection of 4 low velocity zones out of 7. These zones have reduction in velocity of more then 15%, and 1 low velocity zone with a reduction in velocity of more than 10% of the average was detected. Note that 3 out of 7 defects were situated outside the rebar cage; and, therefore, no imaging of defects was possible using CSL or CSLT if the defects did not extend inside the rebar cage.
3. At the time of data acquisition, the concrete in Shaft 4 was one year old. False positive defects, as shown on Figure 10 for the CSLT, could potentially be described as true secondary positive defects occurring as a result of cracking, the age of concrete, debonding of the tube and concrete, and/or installation of the defect itself.

## 7.0 Conclusions of the Research Study

Based on the results obtained from the CSLT-3D™ and the standard CSL, the research investigations were successful in detecting defects and determining the following:

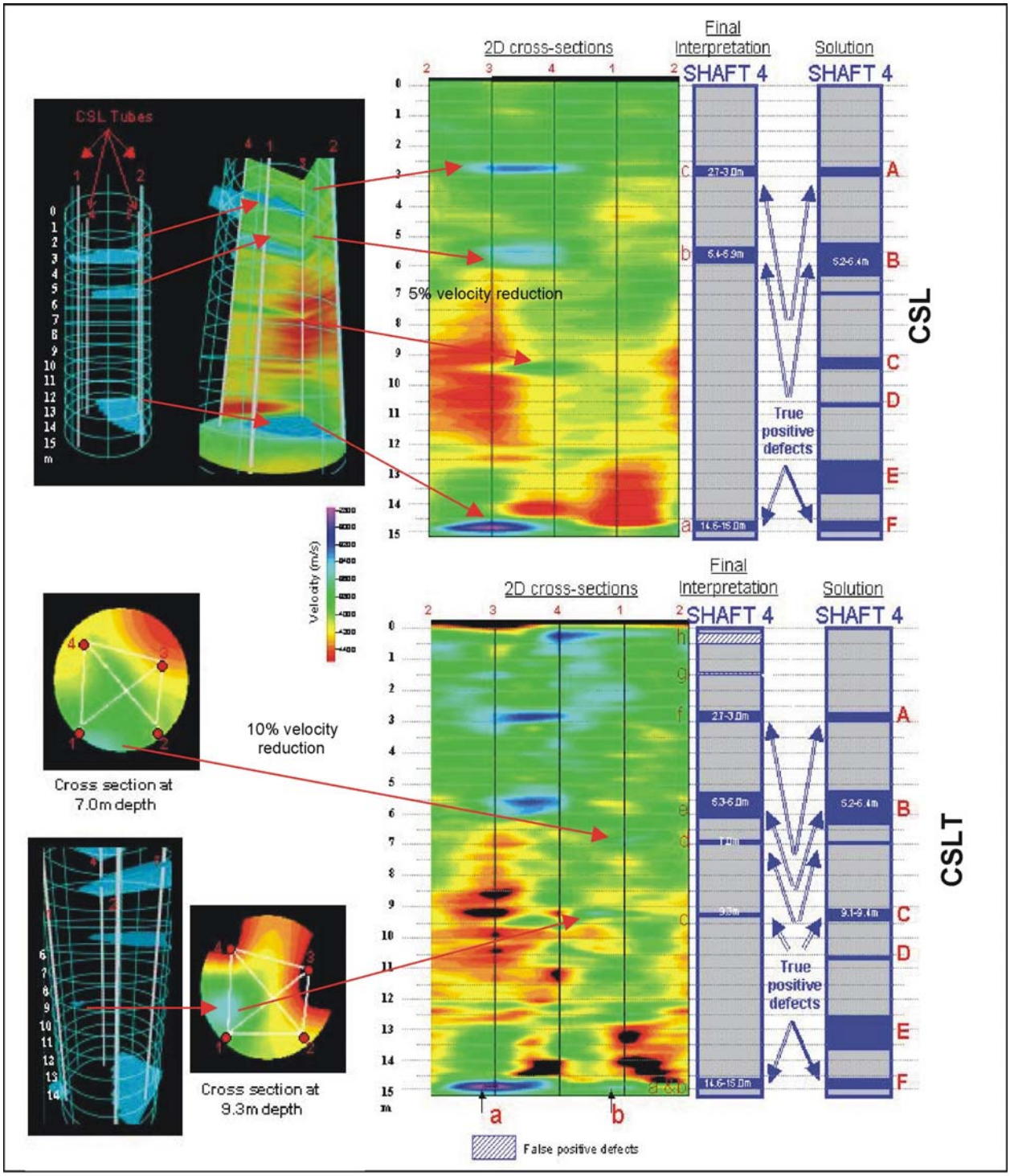



*Figure10. CSL Versus CSLT for the Shaft 4 at the NGES. Blue Colored Velocity Zones Denote More than a 15% Reduction in Velocity (from the Average Velocity) for CSL; Light Blue Zones for the CSLT Denote 10% Reduction in Velocity*

- 2-D and 3-D tomographic processing of the zero-offset CSL data provides an enhanced visualization of the results over standard 1-D CSL logs.
- Multi-offset tomographic imaging provides a more accurate definition of the velocity distribution than standard CSL. Because it better images defects, the percentage drop in velocity is more accurately assessed (defect characterization).
- Multi-offset tomographic imaging provides an accurate spatial definition of defects for confirmation through coring.
- For the narrow wall structures, careful placement of access tubes is required for the structure to be adequately imaged in 3-D.

## 8.0 Benefits of Tomographic Imaging

There are three main benefits of tomographic imaging:

1. Tomographic imaging provides better spatial resolution of defects for confirmation through coring followed by remedial action (if necessary);
2. Tomographic images provides a more accurate correlation between percentage drop in velocity with percentage drop in concrete strength for shaft acceptance criteria; and,
3. Two and three dimensional tomography, when performed routinely, will provide engineers in the owner agencies a tool for assessing the integrity of drilled shaft foundations without further costly delays to construction.

The two-dimensional and three-dimensional tomography representation offered by the CSLT-3D™, provides greater detail of the interior structure, and defects are easier to characterize. A current research effort being conducted at Blackhawk in cooperation with FHWA is planned to relate percentage change in velocity for a defect to changes in shaft concrete strength, which will close the gap for the foundation engineer in deciding to accept, correct (remediate), or reject a given drilled shaft or a wall structure.