

2D & 3D CROSSHOLE SONIC LOGGING TOMOGRAPHY (CSLT) VERSUS CROSSHOLE SONIC LOGGING (CSL) FOR DRILLED SHAFTS

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Abstract

Development of NDT methods has greatly increased in recent years and one of the principal objectives of this development is reliable assessment of the overall integrity and/or the detection of defects within deep concrete foundations. In order to determine the structural stability, other safety issues, and in particular the project progress and success, obtaining accurate and timely information about construction defects is becoming increasingly important for deep foundations.

Crosshole Sonic Logging (CSL) has become the standard practice for testing the integrity of drilled shafts. Although this method has proven to be effective, often the results (typically presented in one-dimensional format), are difficult to quantify and in many cases they are not used by the project engineer. This paper will demonstrate that, at a minimum, CSL data can be processed and presented in two- and three-dimensional (2D and 3D, respectively) format for a shaft.

However, we will show that with improvements to the standard CSL data acquisition geometry and the use of tomographic imaging, a much more accurate evaluation of the shaft can be obtained. Implementing the improvements reveals the true benefit of assessing both geometric and volumetric information about defects within a shaft (if present). The improved method, Crosshole Sonic Logging Tomography (CSLT), allows data to be processed in 2D and 3D space, and in doing so provides much more qualitative and quantitative information about the shaft integrity. The superior accuracy achieved through CSLT is the direct result of three items: data acquisition geometry, a greater amount of data collected, and use of tomography reconstruction algorithms similar to those used in the medical profession for CAT scans. Thus, results from CSLT will be easier to interpret, but most importantly – easier for the site engineer to use.

This paper is intended to present the major differences between assessing shaft integrity using standard CSL testing and data presentation, versus, CSLT testing and data visualization. This will be accomplished by implementing both forward modeling and analysis of field data from a test site.

1.0 Introduction

During the construction process of drilled shafts, defects in the completed shaft can be introduced by different factors (e.g., soil intrusion, concrete quality, rebar cage construction, etc.). As a part of drilled shaft inspection, tests to evaluate the structural soundness, or integrity of the shaft are very important and they can be quite subjective.

CSL testing is generally accepted now as the most accurate sonic technique for eliminating some of the subjectivity in shaft evaluation. The primary function of CSL is to measure the compressional (P-) wave velocity (velocity) distribution for the medium between boreholes. This is accomplished by acquiring high-frequency seismic signals and measuring the travel times through a “first arrival” detection process. Generally, the velocity of a medium at any depth can be calculated by dividing the distance between boreholes by the first arrival time of the seismic (sonic) signal.

When standard CSL tools are used, velocity distribution information can be obtained with two different methods: “zero-offset logging” and “multiple-offset logging”. We will refer to the multiple-offset logging as tomographic logging. As described in this paper, tomographic logging is travel-time tomography which uses first-arrival times to calculate, or reconstruct, the velocity distribution of the medium in great detail. 2D and 3D visualization of the tomographic results can then be used to display the velocity distribution of a shaft.

The tomographic reconstruction method is commonly used in many industries and is just now being applied at the scale of engineered structures. Tomography has been widely used in oil and gas

exploration to image and characterize reservoirs; and, it is even more extensively used in the medical profession to reconstruct images of the body with CAT scans and MRI images.

1.1 CSL versus CSLT

With zero offset logging, CSL's typical mode of operation, obtaining the 2D velocity distribution solution is very simple. One equation is solved for one unknown – the average velocity between a source and a receiver. This information can be used to locate low velocity zones in between boreholes but it cannot determine their spatial distribution or geometry because a single, horizontal crossing raypath is not sufficient. In practice, two or more raypaths crossing each model block (i.e., a pixel) are required to properly image spatial variations of a physical property (e.g., velocity or slowness) from discrete measurements that depend on that property.

Tomography, however, requires multiple offsets above and below the horizontal for 2D velocity reconstruction, as well as multiple offsets with multiple boreholes for 3D velocity reconstruction and imaging. Tomographic reconstruction is almost always iterative. The medium being investigated is divided into blocks and a velocity model is created by tracing raypaths through the blocks. The velocity model is continually modified until matches between the observed travel times (field measurements) and the calculated travel times (synthetic) converge within acceptable error limits.

This paper presents the differences in effectiveness of CSL versus CSLT methods for determining the integrity of concrete in drilled shafts. Also, we will demonstrate the advantage of 2D and 3D imaging for concrete integrity versus standard 1D data presentation. It should be noted that 2D and 3D imaging can be applied to both CSL and CSLT data sets, however the effectiveness of these two methods for detection of defects is demonstrated herein. We believe that improved visualization of the 2D and 3D imaging will help in the understanding of CSLT (or CSL) results. The use of tomographic imaging is presented as progress for development of NDT methods to reliably assess concrete integrity or detection of defects deep foundations.

The importance of accurate data acquisition procedures, data processing parameters, as well as the visualization of the data in order to extract reliable and useful interpretations for a site engineer will also be the focus of this paper.

Results from synthetic modeling of concrete integrity, as well as data from a project test site, are used to demonstrate the benefits of CSLT. Blackhawk Geoservices together with GeoTomo, Inc. (Houston, TX) have collaborated and made an investment to develop TomoSonic, a crosshole tomography software package. Results of efforts to evaluate the software in order to show the capabilities of CSLT for quantitative evaluation of deep shaft foundations are shown in Sections 4.0 and 5.0.

2.0 Planning NDT and evaluating defects for drilled shafts

In general, integrity testing of drilled shafts can be planned or unplanned. Unplanned testing is more costly and the results can be more ambiguous than planned ones. Risk factors of a foundation failure should be assessed and a decision to conduct integrity testing as part of a quality assurance program should be made at the beginning of a project.

Next, at the beginning of any planned NDT program the question of what type of NDT method should be asked. The method most suited to evaluate the structural integrity of drilled shafts depends on the design and construction procedures (O'Neil, W. M., and Reese, C. L., 1999). Acceptance criteria of drilled shaft are based on integrity testing results.

NDT methods for integrity testing of drilled shafts can be classified in two groups: tests which are applied to the shaft head after construction, or "surface methods"; and, tests performed in pre-placed access tubes, or "down-hole (including crosshole sonic) methods".

Over the past 10 years several Class-A prediction programs of drilled shaft defects have taken place in the United States with the objective to test the capabilities and limitations of these various NDT methods. Within these programs, several drilled shafts were constructed with several types of defects integrated in each shaft. Data regarding the number, type, size and location of known defects within the shafts were not released as a priori information for those participants who conducted the surface or down-hole (crosshole) testing. Chronology of the results for the capability and limitations of surface versus down-hole methods is presented in Table 1 (Iskander, M., et. al., 2001).

		Down-hole techniques²
1993	<ul style="list-style-type: none"> - Could not reliably detect defects which are smaller than 50% of the cross sectional area - Can detect bulbs or defects outside the cage where the access tubes are attached 	<ul style="list-style-type: none"> - Are more effective in detecting incompletely concreted shaft bottoms and multiple defects including small inclusions to 12% of cross sectional area - Can not detect bulbs or defects outside the cage where the access tubes are attached
1997	<ul style="list-style-type: none"> - Can result in a large number of false positives - Are incapable of differentiating between necking and bulging - Are highly dependant on operator skill 	<ul style="list-style-type: none"> - Can detect defects which are larger than 15% of the cross sectional area, if access tubes are provided at a rate of one tube per 0.3 m (1ft) of shaft diameter
2000	<ul style="list-style-type: none"> - Were able to identify defects as small as 6% of cross sectional area - Were able to locate up to 3 defects out of 6 or 7 in the same shaft - Had more difficulties to detect large soil inclusions than smaller voids - Had difficulties to detect soft bottoms - Are dependant on equipment and operator skill 	<ul style="list-style-type: none"> - Were generally able to identify defects exceeding 10% of cross sectional area - Were able to identify the length and lateral locations of defects within the shaft - Had more difficulties to detect large soil inclusions than smaller voids - Had difficulties to detect soft bottoms - Are dependant on equipment and operator skill

Table 1. Chronology of the results from several Class- A prediction programs (¹pulse echo and sonic mobility; ²crosshole sonic logging, single-hole sonic logging and crosshole tomography)

When the decision has been made to utilize CSL, then the question about when to employ tomography with the CSL tests becomes somewhat subjective, but objective guidelines are presented later in the paper.

Common defects within shaft are necking, voids, soil inclusions and soft bottoms. By following the FHWA Publication on drilled shafts (O'Neil, W. M., and Reese, C. L., 1999) most common defects that occur in drilled shaft construction are: defects at the base of the drilled shaft, poor concrete along the length of the shaft and inadequate contact along sides of shaft.

2.1. CSL and CSLT data acquisition

Both types of Crosshole Sonic Logging, CSL and CSLT, are clearly down-hole methods. They require access tube installation or attachment to the rebar cage (Figure 1). During CSL and CSLT measurements, velocity information relating to the concrete integrity will be obtained only along the paths that are between the borehole (tube) pairs.

Inside diameter of CSL tubes is typically 2 inches and they have to be water tight. PVC or steel tubes can be installed. In some cases PVC can have poor bonding with the concrete while steel tubes typically do not. Some stainless steel tubes are suitable for a borehole deviation survey, but the survey can be expensive.

Immediately before or after concrete placement (within few hours) the tubes have to be filled with water. To ensure good bonding (coupling) between the concrete and access tubes the external surface should be clean. Additionally, the internal volume has to be clean to allow for undisturbed passage of CSL probes (source and receivers).

In general CSL testing systems have: PC computer, Console, Winch with Depth Wheel and probes (source and receiver) (Figure 2). Ultrasonic source and receiver probes are lowered to the bottom of a pair of access tubes. The two probes are then pulled simultaneously up as to maintain zero offsets.

The typical CSL recording rate is every 0.06 meter (m) (2 inches (in)). The same procedure is repeated for each tube pair combination. For example, the number of CSL logs taken from a shaft that has 4 CSL access tubes is six. Tubes are labeled as 1,2,3 and 4 and CSL logs combinations are: 12, 23, 34, 14, 13 and 24 (Figure 3).



Figure 1. Rebar cage and CSL Tubes of completed drilled shaft



Figure 2. CSL testing equipment a) Console and PC; b) Winch with Depth Wheel (PILELOGs-Full waveform Crosshole Sonic Logging System, InfraSeis, Inc.)

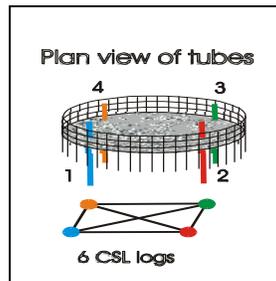


Figure 3. Configuration of CSL logs for the shaft with four CSL tubes installed.

CSL data acquisition can be also performed with the source and receiver set at a specific vertical offset. The probes (source and receiver) are lowered to the bottom of a tube pair, then before the logging begins one of the probes (e.g., the receiver) is lifted or lowered a specific offset distance (or angle) above or below the source level (respectively). Both probes are then pulled simultaneously up to maintain that offset distance. When the receiver is above the source, the records are defined as “positive” offset data. Conversely, when the receiver probe is lower than the source level, the records are defined as “negative” offset data. The offset, either positive or negative, is maintained during that logging run.

Use of multiple tubes and these multiple vertical offsets create the ability to produce true 3D tomographic images of an entire shaft. The step by step procedures for CSL and CSLT data acquisition are presented in Figure. 4 (S denotes source and R denotes receiver).

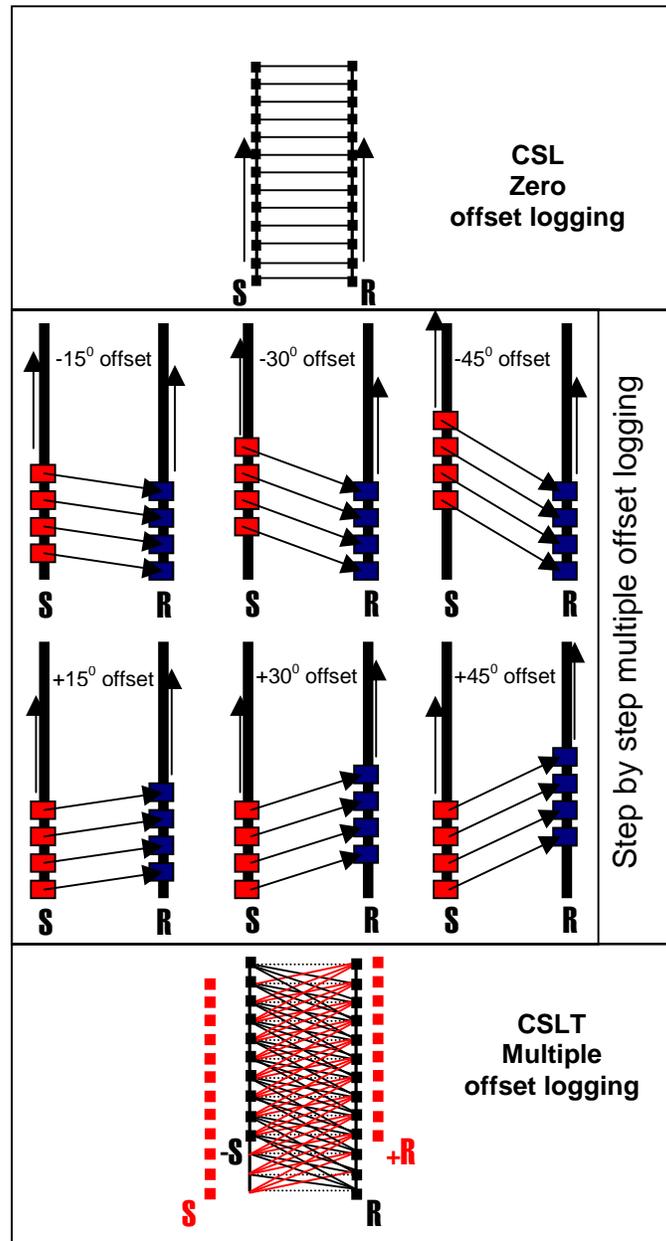


Figure 4. CSL and CSLT data acquisition

When a system with only one source and one receiver is used, CSLT data acquisition requires a little more time than standard zero-offset CSL. Generally, the time difference is about few hours in the field for data collection, but the benefit of performing CSLT will be presented later in this paper. To produce true tomographic images capable of reconstructing a highly accurate image of concrete integrity, the recommended minimum number of offset data sets to be obtained is six (three positive and three negative), plus the zero-offset data.

The acquired CSL data are stored in computer memory. The time required to reduce and process the data needs to be agreed upon by the site engineer prior to final decisions regarding acceptance of shaft integrity. Currently, TomoSonic software has the capability of processing the CSL and CSLT data in near real-time. Providing quality assured, processed, and interpreted data (in 2D and 3D format) *on-site* to the project engineer is the ultimate goal of this effort.

Clearly, to meet the objective of shaft acceptance, it is very important to understand that the accuracy of CSL and CSLT data reduction and processing, as well as the resultant interpretations. A qualified engineer makes the final assessment of shaft integrity, but use of a qualified geophysicist or engineer to present the interpretations is equally important. False positive defects or undetected defects can occur, thus a qualified engineer/geophysicist is recommended for data acquisition as well as data processing and interpretation.

3.0 CSL and CSLT results and shaft acceptance

As previously described, performance of CSL or CSLT requires the use of pre-installed tubes, clean inside and outside tubes, fresh water in the tubes, and accessibility to the tube pairs. Also, uncertainties in the results can be reduced if the person acquiring and interpreting the data has access to inspection records. Such records typically document anomalous performance encountered during shaft installation, often even observations regarding the exact point during the construction process at which such occurrences took place (O'Neil, W. M., and Reese, C. L., 1999).

During the CSL, and especially for CSLT testing, the following items should be considered:

- Deviation of the access tubes. Although borehole directional surveys are not routinely performed as a component of CSL, the tubes can deviate from plumb. Data regarding the amount of deviation, both inclination and direction of the tubes, can be acquired and presented for each borehole used in the shaft to understand the geometry of the borehole configuration with depth. Without deviation information the tube pair(s) separation can be controlling factor in the identification of false positive defects. Borehole directional surveys are required for the majority crosshole surveys where high precision timing of signals is required, and, high precision of the distance between borehole pairs is equally necessary to ensure accurate results.
- Surface distance and azimuth between tube pairs. Measurements of the spatial distance and orientation between all of the boreholes needs to be performed with a high degree of accuracy. Accurate velocity results are a direct result of known borehole mapping at the surface.
- Source/Receiver probe speed. It is critical to maintain constant speed of the probes while retracting them for each run. Poor cable winding and "reel jumps" can introduce false travel-time measurements, thus false velocity information.
- Source/Receiver offset. Maintaining the zero-offset (i.e., equal elevation) for CSL or the other offsets as described above along the length of the shaft is very important to the accurate measurements of travel times along pre-determined raypaths. Poor maintenance of probe offset for the entire length of the shaft is the single most frequent problem introducing velocity errors calculated from travel times.
- Source/Receiver centralizing. The probes need to be centralized within the respective tubes during logging; again, to reduce errors introduced by poorly controlled source/receiver separation.

It can be shown that any the above general aspects of CSL testing, if they are not accounted for or performed properly, can introduce inaccurate results about the concrete integrity (e.g., false positive defect detection). These issues are usually overcome through experience of the data processor and interpreter, but it can be very difficult to distinguish them from actual (e.g., true positive defect detection).

In order to produce reliable results when these issues are not properly accounted for, additional time to pre-process the data as well as final data reduction could be required.

After the logging runs are conducted, the first-arrival times are picked before any further data processing. Small errors in the picked first-arrival times of the zero-offset data will produce slight errors in the velocity field. However, when similar errors are introduced through the picked first arrival times from the any of the offset data records (positive or negative), then errors in the calculated velocity field are typically much greater. Quite simply, velocity artifacts caused by poor processing or mis-identification of first-arrivals could be interpreted as structural features in a shaft.

Based on experience from processing a number of CSL and CSLT data sets, we have found that particular data pre-processing techniques and further evaluation of the arrival time data must be performed in order to produce reliable, quantitative and accurate velocity assessment of a shaft. It has been proven that applying pre-processing techniques and critical evaluation of the field data minimizes false positives identified because of velocity artifacts. Additionally, it maximizes extraction of anomalous irregularities, or defects, within the shaft. Figure 5 illustrates this affect of pre-processing first-arrival times.

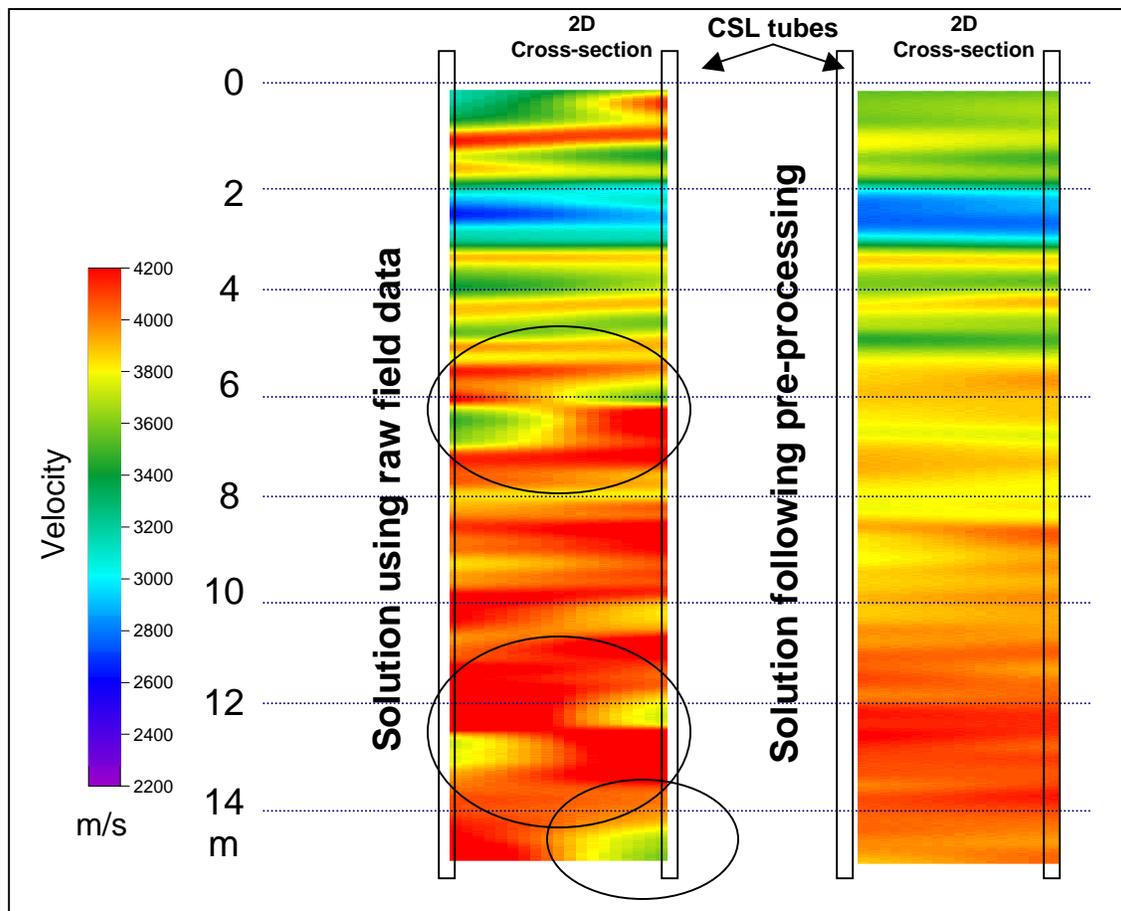


Figure 5. Velocity artifacts caused by poor quality data processing (i.e., solution using raw field data), and reliable data interpretation as the result of good quality pre-processing of the same data set.

Currently, the quantitative evaluation of defects identified by CSL or CSLT is often subjective. That is, what constitutes anomalous velocity reductions as defects from the perspective of the interpreter or site engineer? Five percent, 10 percent, or greater velocity reductions are capable of being detected with quality data acquisition procedures and data reduction/processing methods. But, what is a critical velocity reduction that warrants an identified "defect" to be considered an indication of poor quality concrete throughout a (large) portion of the shaft or smaller isolated defects? As we understand it, these questions

nearly always depend on the contractor's rating criteria for the concrete condition per project. Interaction between the contractor and CSL/CSLT interpreter will facilitate an objective evaluation of defects, and consequently properly selected methods for shaft repair (if necessary) and final acceptance of the integrity of a drilled shaft.

4.0 Data comparison: CSLT vs. CSL

As described and presented in the literature crosshole sonic logging is considered a reliable method in detecting the defects within the shaft between the CSL tube pairs where data are acquired. This is typically done in 1D format, but the data can be presented in 2D (cross-sectional) format. Although, it is clearly documented that defects detected with CSL results cannot define the lateral location, geometry, or provide quantitative information regarding the defect. We believe these information concerning any defect identified are critical to meet the objective of shaft evaluation – but more importantly, to allow for better, more cost-effective repairs to achieve structural integrity criteria established for that project.

This section will demonstrate that crosshole sonic logging tomography has the ability to provide the fore-mentioned detail regarding defects identified. The primary caveat is, that data acquisition and processing procedures have to be performed properly (as described in Sections 2.0 and 2.1).

4.1 Synthetic Modeling

To objectively compare the effectiveness of the CSL and CSLT methods and the presentation of the data 2D synthetic models of drilled shafts were created. The (synthetic) shaft has different sizes, shapes and locations, of defects to compare the capabilities of CSL and CSLT to detect, locate and quantify their properties. Four defects were placed in the synthetic model, each with the velocities of 1500 m/s (4921 ft/s). The overall velocity of the shaft is indicative of good quality concrete with a velocity of 3600 m/s (11,811 ft/s). The CSLT model was built using the zero offset, three positive offsets, and three negative offsets. Offsets have the angles of 15, 30 and 45 degrees. Figure 6 illustrates the synthetic models, the raypaths used to calculate the velocity fields, and the velocity results.

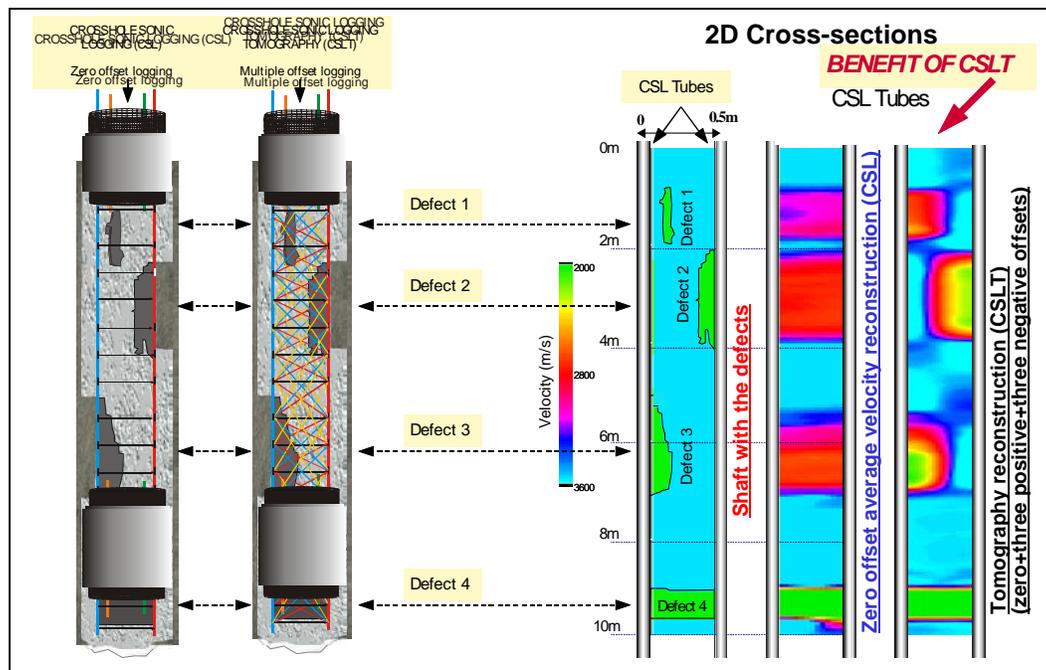


Figure 6. Synthetic shaft model with defects and the velocity results (tomograms) obtained from standard average-velocity zero-offset CSL analysis, CSLT tomographic reconstruction. The results clearly demonstrate the advantage of CSLT over CSL to identify the defects, as well as provide quantitative information about their shape, size and velocity.

Two-dimensional tomographic results presented in Figure 6 for the CSL and the CSLT synthetic data, indicate that CSLT was able to provide much more information regarding the defects. The actual location of the low velocity zone(s) is constrained much better, and the tomogram provides better quantitative assessment of the defect's velocity. It should be noted that the CSL data were processed with tomographic reconstruction methods also (using Tomosonic), but only zero-offset data were used in the analysis.

The 2D CSL modeling was able to reconstruct the 1500 m/s velocity for the defect near the bottom of the shaft (example of a soft bottom defect). However, the velocities of the other defects were over estimated at about 2000 to 2500 m/s and nothing can be determined regarding their position or geometry. It appears that the CSLT results quantified the information about the synthetic defects very reliably (i.e., note the green color in the CSLT cross-section with the green color of the shaft velocity model). The CSLT velocity reconstruction for defect no. 1, near the top of the model shaft, is slightly over estimated compared with the actual velocity. This is a direct affect of the rule that the reliability of quantifying velocity decreases with decreasing the size of the low velocity zone (i.e., defect).

4.2 Tomography and Ray Tracing

How does tomographic velocity reconstruction better define the geometry of defects? The multiple crossing rays acquired by the tomography data acquisition method refract off the boundaries caused by the velocity contrasts, thus information about the geometry (shape and size) can be obtained as well as their lateral location is well constrained. The affect of refraction and multiple crossing rays is illustrated in Figure 7.

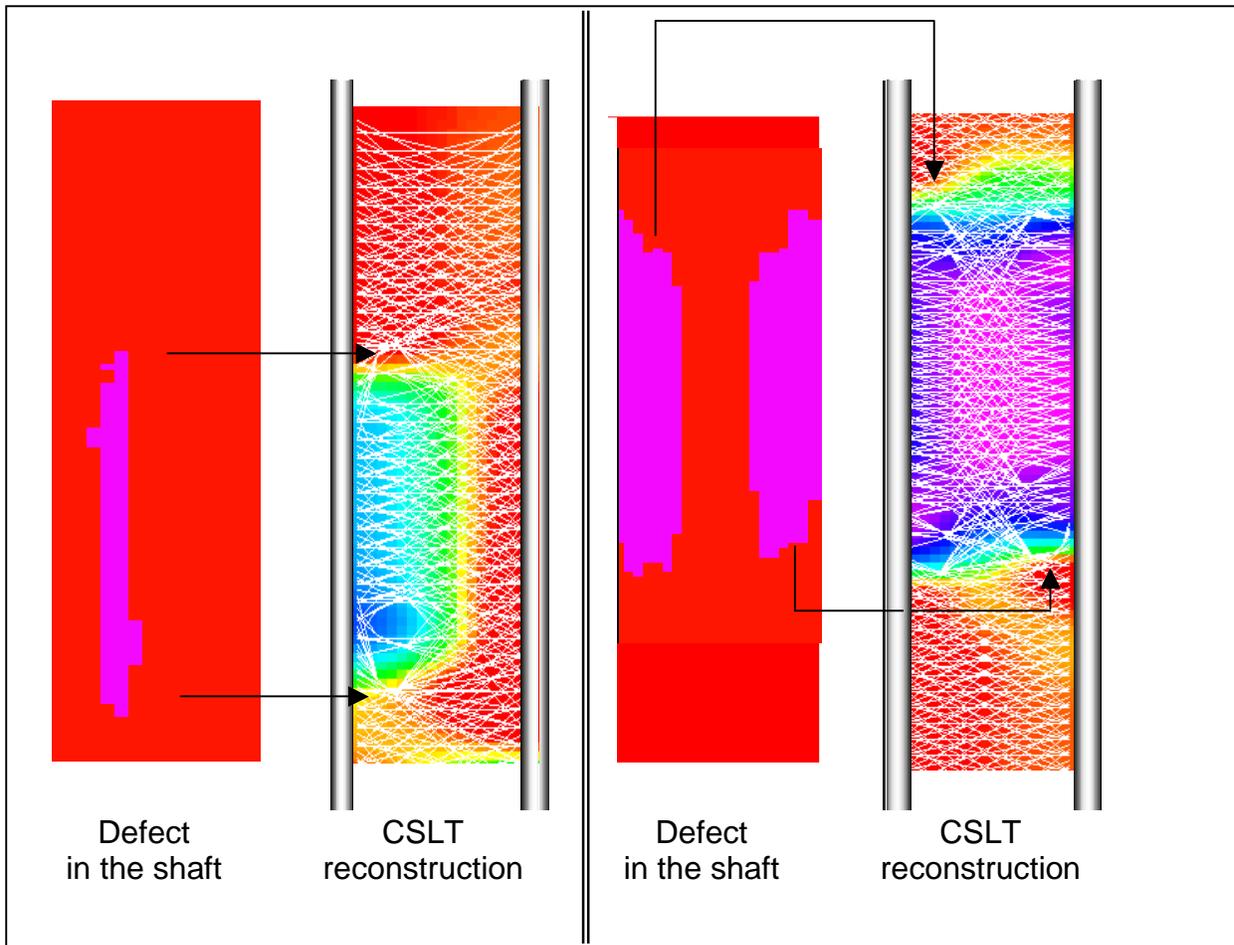


Figure 7. Ray-tracing results with CSLT data acquisition and processing.

4.3 Example Project and Data

The following section presents results from CSL and CSLT testing at a research project site Shaft 4 (Figure 8). The 2001 project report entitled "3D Crosshole Sonic Logging (CSL) and 3D Crosshole Sonic Logging Tomography Imaging (CLSTI) of Shaft 1 and Shaft 4 at the National Geotechnical Experimental Site, Amherst, MA" (prepared by Blackhawk GeoServices) is available through the Federal Highway Administration - Central Federal Lands Highway Division (FHWA-CFHL). Included in the report are: descriptions of the required pre-processing procedures; data reduction techniques; the interpretive results of travel-time tomography processing; and the 2D and 3D visualization techniques applied to the CSLT data.

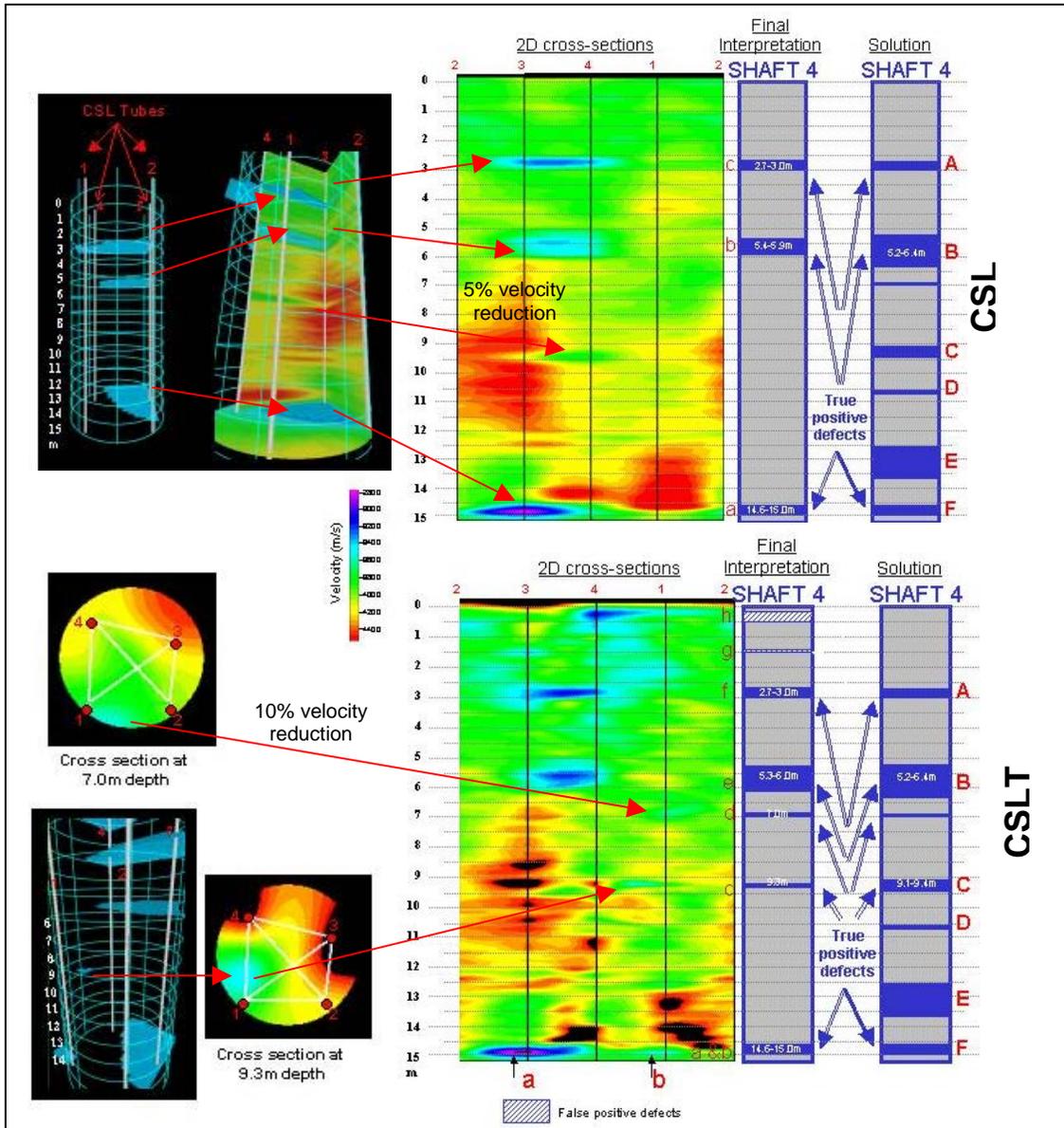


Figure 8. CSL versus CSLT for the Shaft 4 at the NGES. Blue colored velocity zones denote more than a 15% reduction in velocity (from the average velocity) for CSL; light blue zones for the CSLT denote 10% reduction in velocity.

The data were acquired and processed in order to evaluate the integrity of drilled Shafts 1 and 4 at the National Geotechnical Experimentation Site (NGES). CSL data were acquired by InfraSeis, Inc. (Denver, CO) in Shafts 1 and 4 under contract to CFLHD, and Blackhawk GeoServices completed the data processing in the office under separate subcontract to CFHLD. The following objectives were addressed:

- Evaluate the accuracy of the CSL method for detecting known defects in deep-foundation concrete structures utilizing zero-offset data acquisition geometry.
- Evaluate the accuracy of the CSL method for detecting known defects the same structures when utilizing multiple-offset acquisition geometry (i.e., tomography).

The shafts at the NGES were constructed with a number of built-in and different type of defects which were installed for two purposes: assessing various NDT methods; and, evaluating the accuracy of the methods. Data presented in this section are only from Shaft no. 4 using CSL and CSLT techniques described in this paper.

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). Occasionally, low velocity zones were identified that have less than a 10% reduction from the average velocity. Ideally, selection of a “velocity reduction criteria” (i.e., a critical percentage) will depend on the project, on the client needs, and ultimately on design considerations.

The final interpretational results from Shaft 4 at the NGES, presented on Figure 8, 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 in detection of 4 low velocity zones out of 7. These zones have reduction in velocity of more than 15%, and 1 low velocity zone with a reduction in velocity of more than 10% of the average was detected.
- 3) At the time of data acquisition, the concrete in Shaft 4 was one year old. False positive defects, as shown on Figure 8 for the CSLT, could potentially be described as true secondary positive defects occurring as a result of cracking, the to age of concrete, debonding of the tube and concrete, and/or installation of the defect itself.

5.0 2D & 3D Visualization capabilities

Experience shows that good quality visualization of geophysical data is one of the most important factors for the use of final interpreted results. For nearly a decade the interpretational results of CSL have been presented in 1D formats, as shown on Figure 9. It’s believed that these 1D type of presentations and the data they represented were often ignored by the site engineers (personal communications). Basically, this was caused by the uncertainties regarding defect geometry and position within the shaft

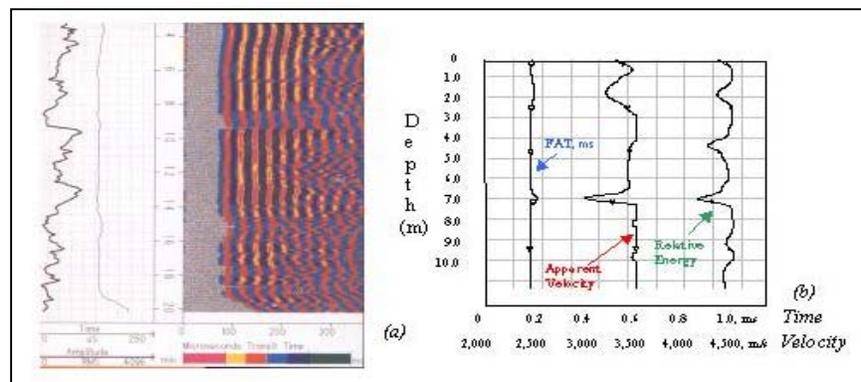


Figure 9. (a) Full waveform stacked traces (InfraSeis, Inc.). (b) CSL log plot – first arrival time (FAT), Apparent Velocity and Relative energy versus depth (GRL & Assoc., Inc.).

New visualization technologies for 2D and 3D data sets allow the presentation format to maximize the effectiveness of results and to minimize the uncertainties in the testing. Figure 10 illustrates an example of these capabilities.

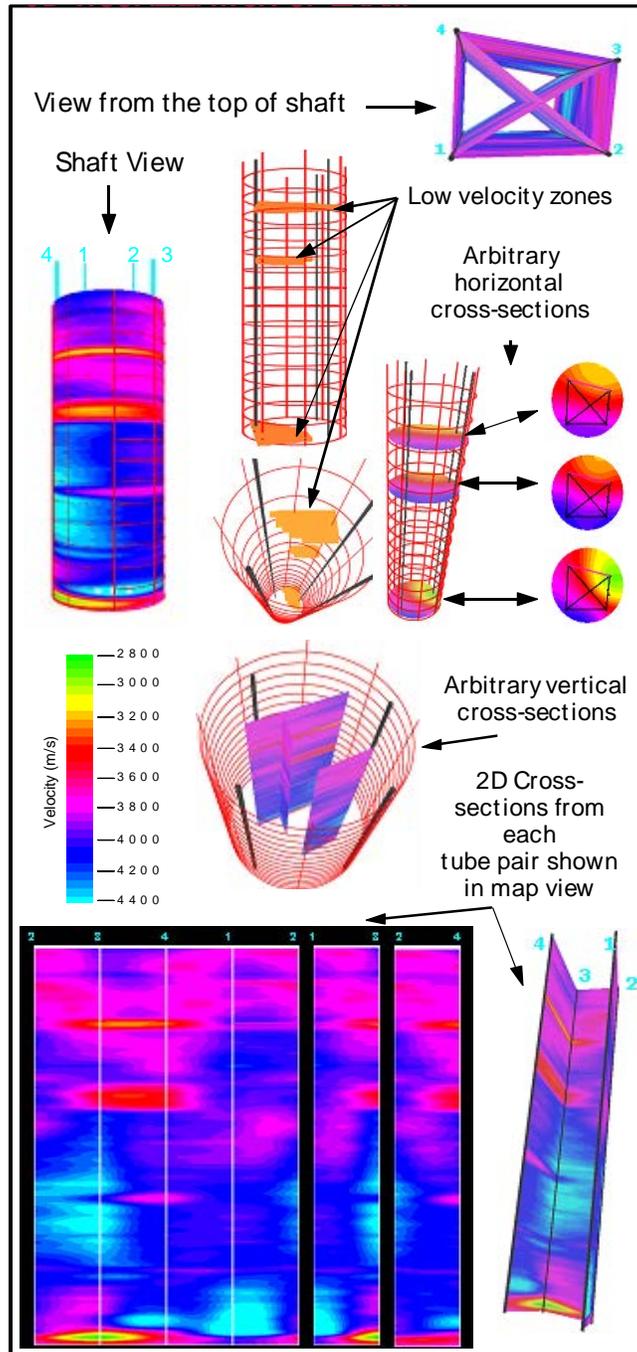


Figure 10. 2D and 3D visualization capabilities for assessing integrity of drilled shafts

CSL and CSLT data can be processed using tomography and presented in 2D or 3D formats. Two-dimensional data processing includes only those data between two tubes and is presented in standard cross-sectional format. Whereas 3D data processing includes data acquired between multiple pairs of tubes. If zero-offset CSL data are acquired between two tubes, then 2D data processing results in 2D zero-offset average velocity data between those two tubes. With data acquired using zero-offset

logging for the entire shaft in multiple tube pairs, the results can be presented as 3D zero-offset average velocity for the entire shaft. From 3D zero-offset data interpretations, selection of any 2D cross-sections is available for evaluation of the shaft.

As shown, with tomography data acquisition procedures and when data are acquired between two tubes, the addition of more raypaths allows true 2D travel-time tomographic reconstruction to be achieved. Use of multiple tube pairs and multiple offsets produces true 3D tomography results. From 3D tomographic data interpretations, selection of any 2D cross-section (between tubes or arbitrary slices) allows significantly better assessment of the shaft.

6.0 Conclusions

The following conclusions can be drawn:

- When the risk factors for foundation failure have been evaluated, the decision to conduct down-hole NDT as an integral part of the quality assurance program should be made at the beginning of a project. Unplanned testing is more costly and the results can be more ambiguous than planned ones.
- It is accepted in the industry that using down-hole methods is superior over surface methods for detecting, locating and evaluating the presence of defects within completed drilled shafts; and, that CSL and CSLT methods are the most definitive sonic methods for evaluating the shaft area and volume for definition of defects, especially between the installed tubes.
- Using 2D and/or 3D tomography reconstruction techniques with standard CSL data helps quantify and visualize the zero-offset data better than the typical 1D CSL interpretational procedures.
- Applying CSL in a true tomography procedure – defined herein as CSLT, is far superior than zero-offset CSL procedures for defining quantitative information about defects (if present) within drilled shafts. CSLT only requires multiple raypaths (i.e., source/receiver offsets) be acquired and the travel-times be used in the velocity reconstruction. The detailed information provided by the CSLT regarding geometry, position and velocity of the defect clearly will assist in assessing the integrity of the shaft and methods to repair the defect, if necessary.
- The capability to use new 2D and 3D visualization techniques to present either CSL or CSLT results will significantly improve a site engineer's ability to accept or reject the shaft under investigation based on design criteria for vertical and lateral loads; additionally, the capability to present these high-resolution data on-site in near-real time will enhance the use of this product as well as allow construction schedules to be maintained.
- The quality of CSL (and CSLT) data acquisition, data reduction (including pre-processing if necessary), and interpretation are directly tied to the reliable evaluation of a shaft's integrity.
- Understanding that the compelling question to evaluate a shaft's integrity is how low velocity zones (i.e., defects) affect the vertical and lateral carrying capacity of the designed foundation is at the heart of this comparative study. We believe that it is very important to establish criteria for the characterization of irregularities (e.g., percent reduction in velocity, cross-sectional area, or volume) within a shaft before final decisions are rendered from CSLT results regarding a shaft's integrity.
- Interaction between the construction contractor and interpreter of CSL or CSLT data must begin with a introduction of the shaft construction process at a given site. Also, if or where any unusual factors were encountered during construction of the shaft. This interaction and integration of site-specific information must be continued through the process of shaft repair to improve the CSLT interpretation and meet the objective of final acceptance of the shaft.

7.0 References

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