Crosshole Sonic Logging and Tomographic Velocity Imaging of a New Drilled Shaft Bridge Foundation

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ABSTRACT

Crosshole Sonic Logging (CSL) has come into widespread use for quality assurance of the concrete placement in drilled shaft bridge foundations, particularly when they are drilled using wet-hole drilling methods due to the risk of concrete contamination. The paper first presents a brief review of the CSL method of measuring the speed of sound between water-filled cast-in-place access tubes for example results from sound and defective drilled shafts tested in consulting and research projects.

The paper next discusses the use of Crosshole Tomographic (CT) velocity imaging of concrete defects in shafts. The CT method is discussed and illustrated for color velocity tomograms of defects in actual bridge shafts and for constructed defects in research shafts. A final case history is presented with the results of CSL and CT of a new drilled shaft foundation for a pedestrian bridge. The ability of CT to provide 2-D and now 3-D velocity images of a potential defect provides excellent data on the shape and severity of CSL anomalies.

INTRODUCTION

New concrete shaft foundations are often poured in wet holes in which at least a portion of the shaft is below the groundwater level. The methods used for properly placing concrete in a wet hole pose a risk of concrete contamination from adjacent soil intrusion or collapse and risk of concrete thinning by accidental increase of the water-to-cement ratio. Non-destructive Evaluation (NDE) is typically performed to quickly and accurately locate and assess possible foundation defects and to describe their size, shape, and severity. Acoustic methods are the most widely used techniques for testing foundations for defects; the two most common methods are Crosshole Sonic Logging (CSL) and Crosshole Tomography (CT). Both CSL and CT have high spatial resolution and have proven to be accurate in research and construction cases. Descriptions of the test methods, example results, and a case history is given below.

CROSSHOLE SONIC LOGGING (CSL)

Crosshole Sonic Logging (CSL) is the quickest of the two acoustic test methods and provides an initial assessment of the integrity of the foundation. With the CSL test, defect height, depth location, and approximate lateral location can be determined. In the case that no defects are found using CSL, Crosshole Tomography (CT) is rarely performed because little additional information can be obtained. The CSL method is described and example data are given as follows.

Crosshole Sonic Logging (CSL) Test Method

The CSL test is a downhole method for quality assurance testing of drilled shaft foundations and concrete slurry walls. Access tubes, typically PVC or steel, must be cast-in-place in the concrete during construction or coreholes must be cut to permit logging as illustrated in Fig. 1. For a CSL test, logging involves passing an ultrasonic pulse through the concrete between source and receiver probes, which are located at the same depth in water-filled tube pair or hole pair as the probe cables are pulled back to the surface over a depth measurement wheel. The CSL method thus tests the quality of the concrete lying between a tested pair of tubes.

In the CSL test, the source is excited by a high voltage pulse every 0.2 feet, while the receiver response and measurement depth are simultaneously recorded for each measurement. To minimize noise, the receiver response is electronically bandpass filtered around the receiver's resonant frequency. Data from the receiver probe is then recorded and processed by a PC-based sonic logging system.

Analyses to evaluate the integrity of the concrete include measurement of wave travel times between the source and receiver, calculation of corresponding wave velocities, and measuring receiver response energies. Longer travel times and corresponding slower velocities are indicative of irregularities in the concrete between the tubes, provided good bonding is present between the tubes and concrete. The complete loss of signal is indicative of a

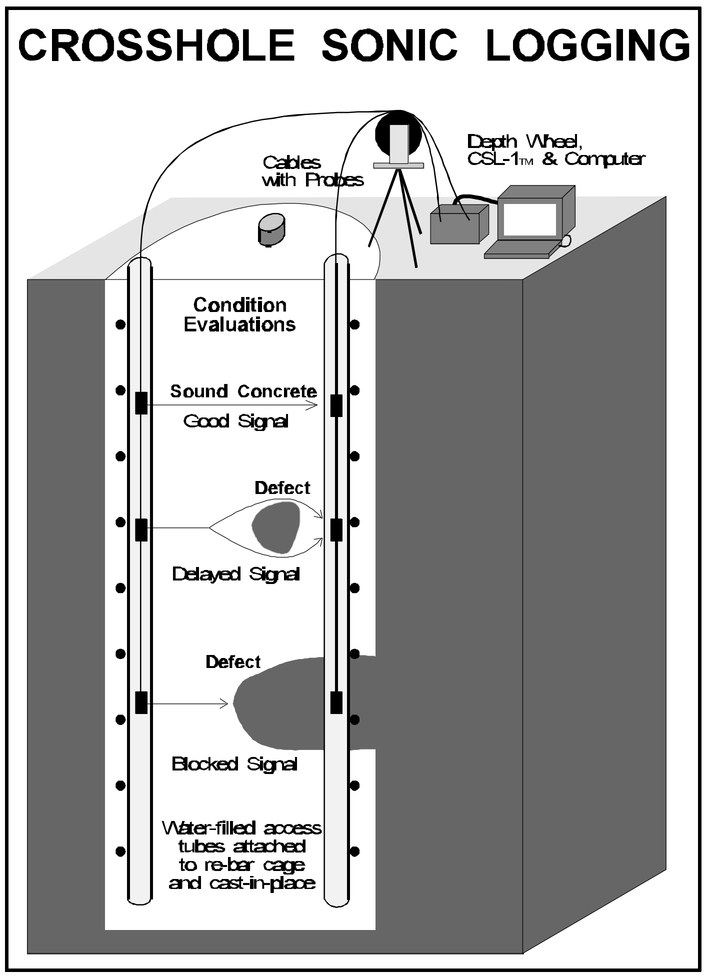


Figure 1 - Crosshole Sonic Logging Test Method

significant defect in the concrete between one or more tube pair combinations.

Desirable results show consistent pulse arrival times with corresponding compression wave velocities that are reasonable for concrete. Defects such as contaminated, weak concrete and soil intrusions will result in delayed arrivals (slower velocity) or no arrivals in the defect zone. The signal energy level is a secondary indicator of concrete quality with low energy indicating poorer quality concrete. The wave velocity increases with time in concrete as it matures, particularly in the first few days of curing.

Example CSL Results

Initial compressional wave (P wave) arrival times are automatically picked by the CSL software program or manually picked by the user. The arrival times are then plotted versus depth to produce a CSL log like that shown in Fig. 2 in what is known as a FAT plot (First Arrival Time). Fig. 2 shows the CSL log and a single time domain signal for a sound (no anomalies) concrete shaft foundation,

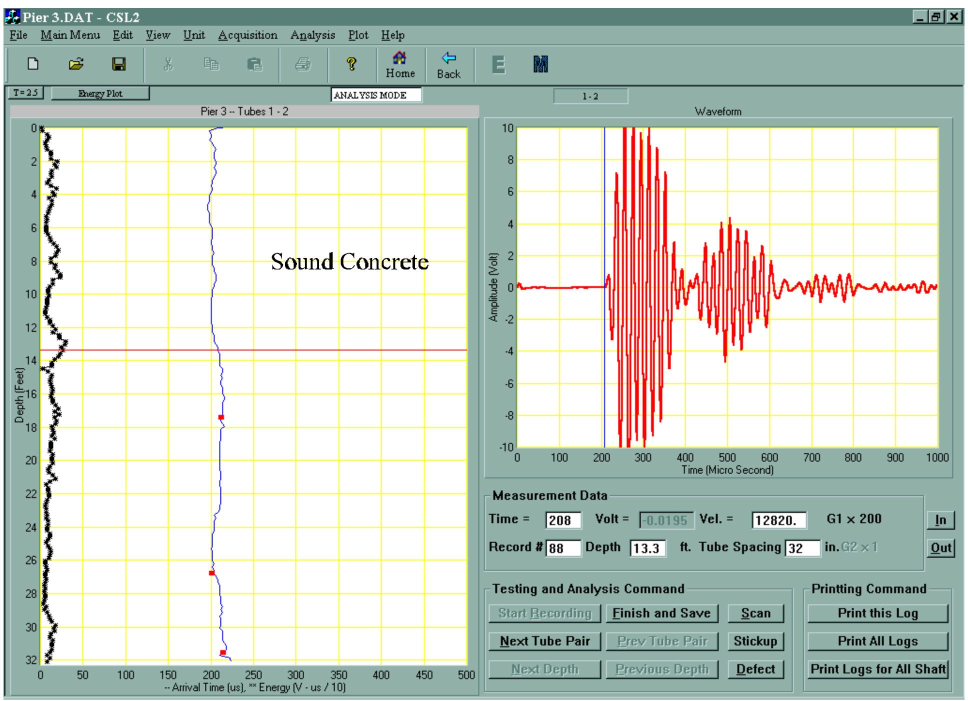


Figure 2 - CSL log for a SOUND shaft foundation (left) showing the first arrival time (blue) and energy plots (black asterisks). A single recorded time domain signal is shown in red (right) for the red cursor depth position in the log.

32 ft long, from a consulting project. First arrival times are plotted in blue (light line) and receiver output energy is plotted in black asterisks. The time domain signal recorded at a depth of 13.3 ft below the top of the shaft is displayed on the right side of the screen in red and the first arrival time is marked with the vertical cursor. The tubes used for the CSL test recorded in Fig. 2 were 32 inches

apart. At a depth of 13.3 ft, the velocity of the concrete, V_c, can be determined by:

$$V_c = D / t_p = 32 \text{ inches} / 208 * 10^{-6} \text{ s} = 12{,}830 \text{ ft/s} \quad (1)$$

where D is equal to the tube spacing in inches and t_p equals the first arrival of the compressional wave energy (P wave).

Figure 3 shows the CSL log for a defective concrete shaft foundation, approximately 54 ft long. The area labeled “Debonded Region” indicates where the PVC access tubes were debonded from the concrete. Debonding conditions between tubes and concrete can sometime occur in a shaft. Tube debonding conditions can be due to various causes. The most common cause of tube debonding is initial tube expansion during the curing process due to heat from concrete hydration followed by contraction of the tube as the concrete cools. Tube debonding conditions are more common in PVC tubes than steel tubes because plastic is much more thermally expansive than steel or concrete. To minimize tube debonding, water must be added to the tubes immediately after concrete placement. Mechanical disturbance to the tubes (such as impacting the tube) should be avoided to minimize debonding. No shaft integrity information can be obtained from the CSL logs in debonded regions and different NDE methods must be pursued.

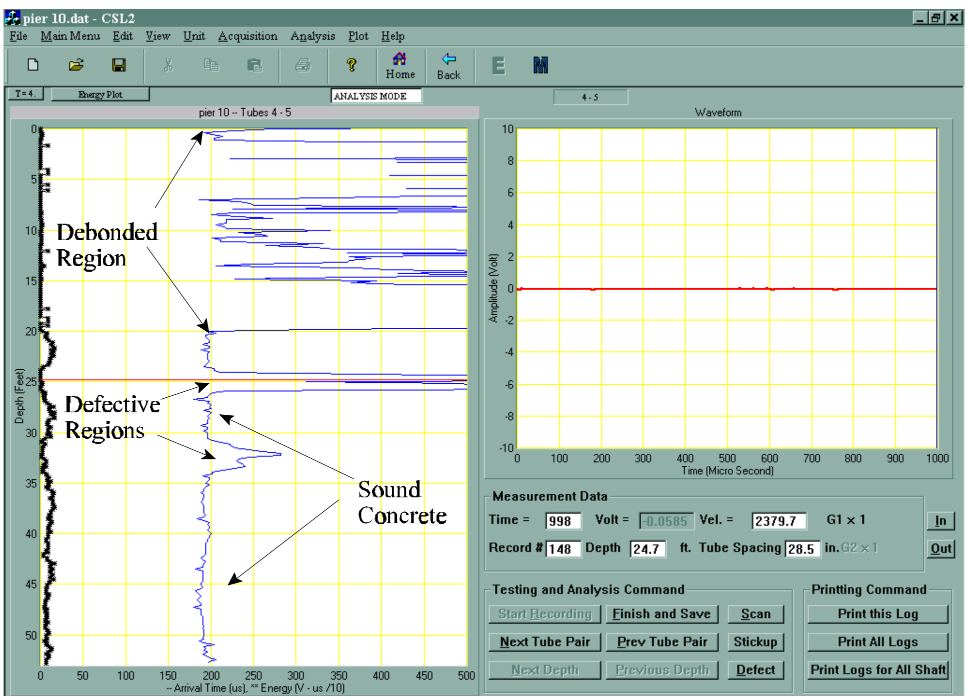


Figure 3 - CSL log for a DEFECTIVE shaft foundation (left) showing the first arrival time (blue) and energy plots (black asterisks). A single recorded time domain signal is shown in red (right) for the red cursor depth position on the log.

Two defects, upper and lower, are shown deeper in the shaft at approximate depths of 23- 27 ft and 31- 34 ft, respectively. These defects were initially reported as anomalies because the signatures of both the FAT and energy plots deviate from the normal trend of the shaft, but without coring it is uncertain whether the anomaly is a defect or due to other causes (debonding for example). The waveform on the right corresponds to the depth of 24.7 ft indicated by the cursor on the log in the middle of the upper defect. Notice there is relatively no signal recorded compared to that in Fig. 2 for the sound shaft. This observation is supported by the facts that the FAT for this depth cannot be determined neither automatically nor manually and the energy for this depth is near zero. In this case, no energy was recorded by the deceiver. The FAT's for the lower defect were recordable but were later in time than the normal trend of the FAT's due to the defect. This shaft was cored and both defects that were discovered with the CSL testing were encountered. The upper, more severe defect was found to be a void and the lower defect was found to be due to soil intrusion.

CROSSHOLE TOMOGRAPHY (CT)

Crosshole Tomography (CT) is an imaging method analogous to CAT-scanning in the medical industry and uses acoustic waves. CT testing is often performed after the CSL testing has been performed to obtain more information about the size, shape, location, and severity of a suspected defect in a shaft. CT data collection is intense and the procedure is relatively slow compared with CSL. The spatial resolution of CT is much higher than that of CSL and an actual image of the shaft is produced. A description of the CT test method is given below.

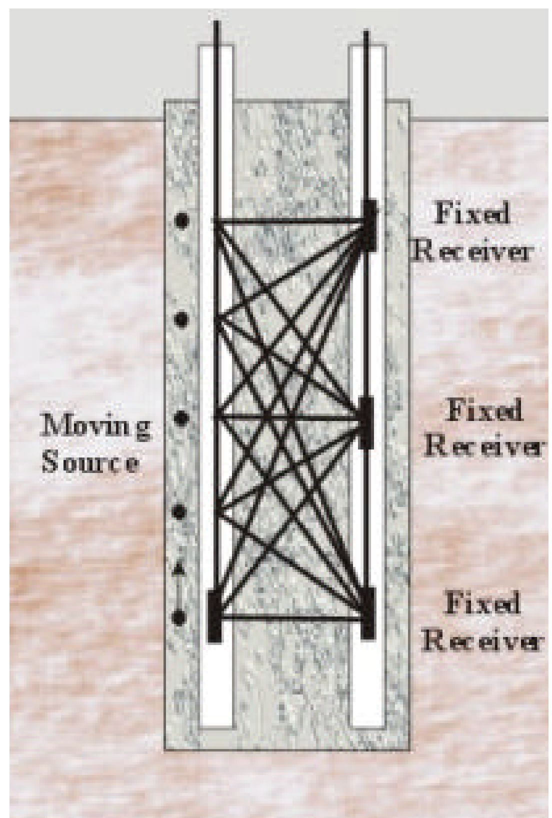


Figure 4 - Crosshole Tomography (CT) test schematic for concrete foundation quality assurance

Crosshole Tomography (CT) Test Method

The CT method uses the same equipment and access tubes as the CSL method. For CT testing, acoustic data are collected for many receiver and source combinations at different depths (Fig. 4) whereas CSL testing is for source and receiver positions at the same depth or horizontal plane. For a typical CT data set, thousands of raypaths are generated for tens or hundreds of source-receiver location combinations.

Crosshole Tomography is an analytical technique which uses an inversion procedure on the first arrival time data of compressional or shear wave energy that can produce ultrasonic pulse-velocity based images of a 2-D or 3-D concrete zone inside a foundation or the entire foundation. The test region is first discretized into many cells with assumed slowness values (inverse of velocity) and then the time arrivals along the test paths are calculated. The calculated times are compared to the measured travel times and the errors are redistributed along the individual cells using mathematical models. This process is continued until the measured travel times match the assumed travel times within an assumed tolerance. The end result is a 2-D or 3-D image (contour) of the internal structure of the foundation, revealing sound versus defective areas.

CSL AND CT CASE HISTORY

Olson Engineering, Inc. has performed CSL and CT testing on shaft, pile, and footing bridge foundations for consulting and research purposes. A case history on a project performed on a bridge shaft foundation is presented below.

Bridge Shaft Foundation CSL and CT

CSL tests performed on a concrete shaft foundation for a pedestrian bridge revealed an anomaly from approximately 36-39 ft below the top of the shaft in four logs. The CSL tube pairs in which the anomaly was identified were 2-3, 3-4, 1-3, and 2-4 for the 4 tube shaft and the acoustic wave velocity reductions of the anomaly ranged from 14% - 26%.

Crosshole Tomography testing was performed to more exactly determine the size, shape, and location of the anomaly. The four 2-D tomograms are shown in Fig. 5 for the four tube pairs tested. The 2-D tomograms are vertical slices of the shaft in between the respective tube pairs and plot acoustic wave velocities of the shaft materials as color contours. The color contours were designed to show sound material in green and defective materials in red, orange, and yellow. Areas with low acoustic wave velocity indicate either weaker concrete materials or soil/subsurface materials. The perimeter tomograms, 2-3 and 3-4 in Fig. 5a and 5b show the defect to be most pronounced. It is only slightly visible in the diagonal internal logs for tube pairs 1-3 and 2-4 in Fig. 5c and 5d.

A compilation of all the 2-D tomogram data was used to generate a 3-D tomogram. Figure 6 presents horizontal depth slices of the shaft from the 3-D tomogram and gives a complete summary of the size, shape, and location of the defect. The white areas in the depth slices indicate areas of no acoustic wave ray path coverage because no CT tests were performed in tube pairs which CSL showed sound concrete between.

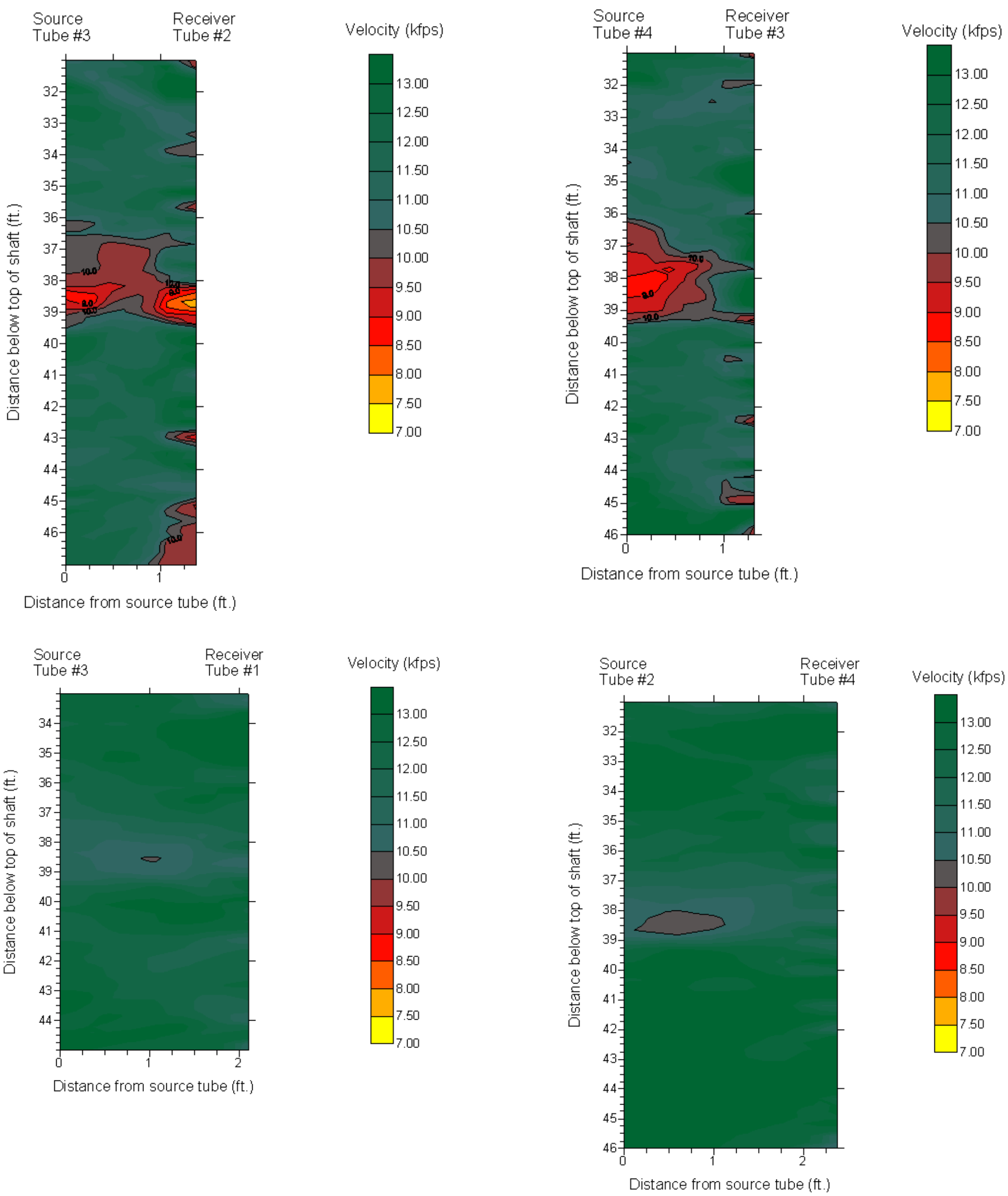
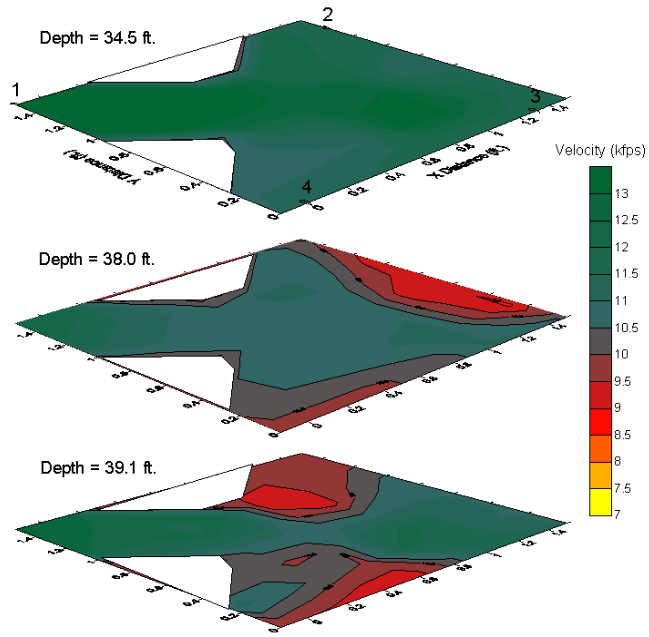


Figure 5 - 2-D Tomograms for the shaft foundation generated by CT testing



White areas indicate no ray coverage.

Figure 6 - Depth slices generated from a 3-D tomography data set

CONCLUSIONS

The use of Crosshole Sonic Logging (CSL) to identify concrete defects in drilled shafts for wet holes has become a proven QA method for most DOT's in the U.S. Now, 2-D and 3-D Crosshole Tomograms (CT) are practical and powerful for use in imaging CSL anomalies to characterize the size, shape, extent, and severity of potential defects.