Detecting Location of Construction Defects in Drilled Shafts Using Frequency Tomography Analysis of Cross-hole Sonic Logging

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Cross-hole Sonic Logging (CSL) is the standard method used in evaluating the integrity of deep foundations for bridges, such as drilled shafts, and is based on travelling ultrasonic waves between probes in parallel tubes. Several studies have used arrival time and wave speed, such as in cross-hole tomography, to detect construction defects in drilled shaft foundations. A processing method for three-component wide-band CSL data is presented—named Frequency Tomography Analysis (FTA). It uses changes in color of the frequency amplitude of the received signal in the location of defects. The method transfers time-domain data to frequency-domain data of the signals propagated between the tubes using Fast Fourier Transform (FFT). The method is performed after a CSL test has determined the high probability of an anomaly in a given area. The procedure improves the location accuracy and further characterizes the features of the defect. The new technique is validated experimentally using two drilled shaft samples constructed with foam pieces inserted throughout the length of the shaft inside the rebar cage before concrete placement, to replicate construction defects. FTA is then utilized after the CSL tests to detect the location of the defects. The technique proves to have a very high resolution and can determine the exact location of any void or defect inside the rebar cage of a drilled shaft. This provides a significant improvement to current techniques used in quality control during construction of bridges.

INTRODUCTION

Several different construction methods exist today for the construction of drilled shafts (O'Neil and Reese, 1999). The most widely used method today is the wet method, whereby shafts are cast under wet conditions using slurry in order to keep the borehole open during drilling and casting of the concrete. The nature of this process leads to different types of defects in the constructed shafts such as necking and voids or soil intrusions. These defects can result from collapse in soft strata, falling of boring spoils from the surface, tightly-spaced rebar, or the existence of dry chunks of concrete.

Sarhan et al. (2003) showed that defects occupying up to 15% of the drilled shaft's cross section could remain undetected. Camp et al. (2007) found that, out of 441 drilled shafts tested on multiple projects in South Carolina, about 75% of the projects had at least one shaft containing a defect, and 33% of all shafts tested contained at least one defect. Such defects in the integrity of the drilled shaft can affect their performance and ability to carry the large loads they are designed for. For this reason quality control is a critical factor in the construction of this type of deep foundations. Several methods are currently used to perform nondestructive testing (NDT) of deep foundations. CSL has become a common and reliable method among the most usual methods of NDT testing. ASTM D6760 (2008) provides a complete guidance for the CSL test. Chang and Nghiem (2006) showed that defects near the top of a drilled shaft will significantly affect its structural capacity.

The CSL method is discussed in details by Baker, et al. (1993) and O'Neill (1999). CSL is a type of NDT that is based on the propagation of ultrasonic waves between two or more access tubes inside the reinforcing steel cage. CSL has been shown to be the most reliable technique for assessing the integrity of in-place constructed deep foundation elements such as drilled shafts. Iskander, et al. (2003) studied drilled shafts with built-in defects located in various sections within the shafts and included voids and soil inclusions occupying 5 - 45% of the cross section. The study concluded that methods such as CSL and cross hole tomography are generally able to identify defects exceeding 10% of the cross sectional area.

Several variations of the CSL test have been developed over the years. One specific variant of the CSL is the Cross-hole Tomography (CT) test that is performed by keeping the receiver at a fixed position and raising the hydrophone while it is emitting sonic pulses. As in the CSL test, the arrival times from the hydrophone to the receiver probe are recorded, and the ray-paths make the three dimensional modeling of the suspect shaft possible. Olson and Hollena (2002) used CT velocity imaging method of concrete defects in drilled shafts by producing colored velocity tomograms of the defects. Some applications of CT have been reported by Tronicke (2002) in hydrological applications, and by Fullagar, et al. (2000) in mining application.

OBJECTIVES AND APPROACH

The purpose of this study is to present a new method developed to detect the exact location of the defects after performing the CSL test. To accomplish this objective, two drilled shaft samples were constructed with prefabricated voids and tested seven days after concrete placement using CSL. The results were evaluated using signal processing. An improved detection method was used that considers not only the traditional arrival time changes but also the signal strength and frequency amplitude of the signal reduction to improve the location accuracy.

Test Samples. The test specimens 20 inches (50.8 cm) diameters, and a length of 4 feet (122 cm). The formwork had a length of 48 inches (122 cm), a width of 48 inches (122 cm), and a height of 48 inches (122 cm). A sona-tube with a diameter of

20 inches (50.8 cm) and a length of 4 feet was used as a casing around the drilled shaft. The shaft was longitudinally reinforced with six (6), No. 10, Grade 60, steel bars equally spaced around the perimeter. The horizontal ties used were No. 4 and were spaced at 4 inches on center. The clear cover on all steel was 1 inch. The CSL tubes that were installed inside and outside the cage were galvanized tubes with 2 inches (5 cm) inside diameter. Figure 1 shows a schematic of the test samples.

The specimens had four access galvanized tubes inside the cage and four tubes outside the cage. Each galvanized tube was fixed at the end and at third points throughout the length of the shaft. For all the specimens, the outside galvanized tubes were installed and aligned to be 3 inches (7.5 cm) away from the edge of the shaft. Dry limestone with a unit weight of 80 lb/ft^3 was placed and compacted in three lifts outside the sona-tubes. Concrete with 5,000 psi compressive strength was placed inside the sona-tubes. The sona-tubes were then removed and the concrete vibrated inside the sample shafts to create a perfect bond with the soil. The specimens were tested one week after concrete placement.

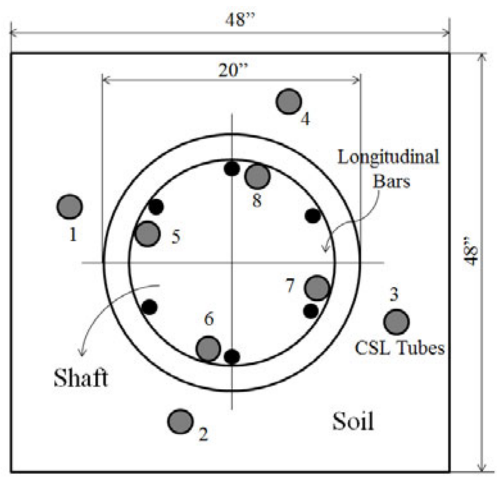
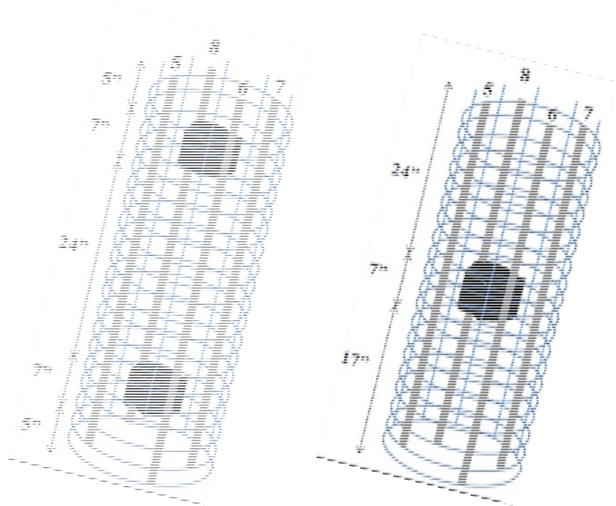


Figure 1. Plan View of Test Specimens with CSL Tubes

Defect Modeling and Test Procedure. Based on common void sizes from the field and from literature, the built-in voids placed in the test shafts occupy about 20% of the gross cross sectional area. One test shaft had prefabricated voids at the top and the bottom of the shaft, and another sample with a built-in void at the middle of the shaft's length—both inside the rebar cage. Foam pieces measuring 7 inches (17.8 cm) in length were used to simulate the void defect, and were secured in place by wire ties to the steel rebar cage. The defects in the test shafts are situated within the test shafts as shown in Figure 2.

A standard CSL test as per ASTM 6760 Standard Test Method for Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing (ASTM D6760, 2008), was conducted between the inside tubes after being filled with water to ensure good acoustic coupling. Signal processing was used to analyze the data obtained. Six CSL tests were performed between the tubes inside the concrete (tubes 5-6, 5-7, 5-8, 6-7, 6-8 and 7-8) one week after concrete placement. Also, four CSL tests were performed between the inside and outside tubes (tubes 1-5, 2-6, 3-7, and 4-8).

Signal Processing On the CSL Test Results. After performing the CSL test, the data acquisition signal graph was recorded. Time domain data can easily be obtained from the data acquisition signal. Figure 3 shows the data acquisition signal for two separate CSL tests on the drilled shaft sample at the height of 31.5 inches, between two tubes inside the concrete (C-C). It can be seen that both tests have exactly the same first arrival time (FAT).



(a) Specimen 1 (b) Specimen 2

Figure 2. Constructed Voids inside the Caging Through the Length of the Shaft Specimen

Time domain contours do not allow for the detection of the exact location of the defects. The time domain data was therefore converted to frequency domain data using Fast Fourier Transform (FFT), in order to obtain the frequency domain tomography. Discrete Fourier Transform (DFT) is a specific kind of discrete transform, used in Fourier analysis. It transforms one function into another. The frequency domain curves were de-noising using wavelet decomposition and fitted with a tenth degree polynomial as shown in Figure 4. It can be seen that both have almost the same maximum amplitude of signal. It also shows that the maximum amplitude of the signal is around 7.0×10^{-4} when both tubes are placed inside the concrete. Since limestone material is not as dense as concrete, it can be said that the FAT for a concrete-soil test is much higher than that in the concrete-concrete test; this is because the ultrasonic wave travel time is much higher.

It is difficult to identify the frequency components by looking at the original signal. Converting it to the frequency domain, the discrete Fourier transform of the noisy signal *y* is found by taking the FFT of the signal. The FFT utilizes an algorithm to perform the same function as the DTF, but in much less time.

Plots similar to Figure 4 were used to obtain the maximum amplitude of the signals, which were 7.2×10^{-4} for C-C test and 2.8×10^{-4} for C-S test. Figure 4 also shows that in the frequency domain, both C-C tests have almost the same frequency domain data and the same maximum amplitude of signal. Results from two C-S tests show that for one test with concrete thickness of 5 inches, the maximum amplitude of the signal is about 8×10^{-5}, and for other test with concrete thickness of 4 inches, it is

6.5×10^{-5}. The concrete thickness can therefore be correlated to the maximum amplitude of the signal. This means that with the change in the concrete thickness due to presence of void inside the cage, the frequency domain and maximum amplitude of the signal will change.

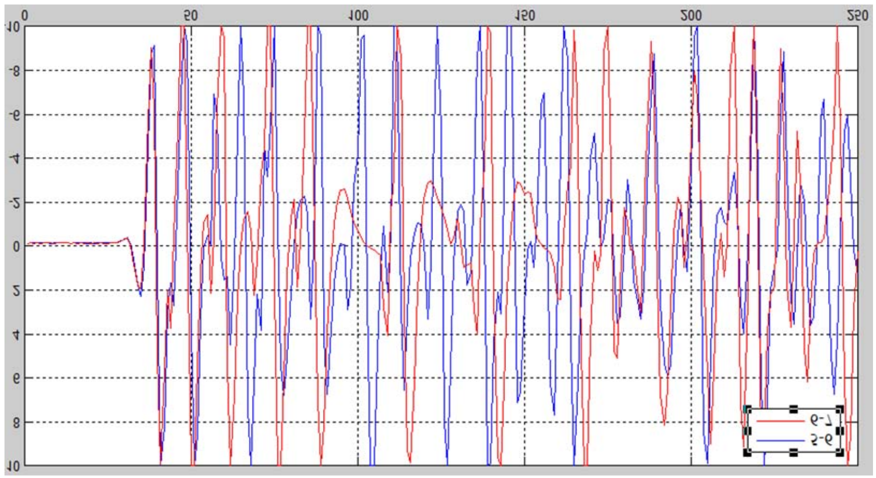


Figure 3. Time-Domain (5-6 and 6-7)

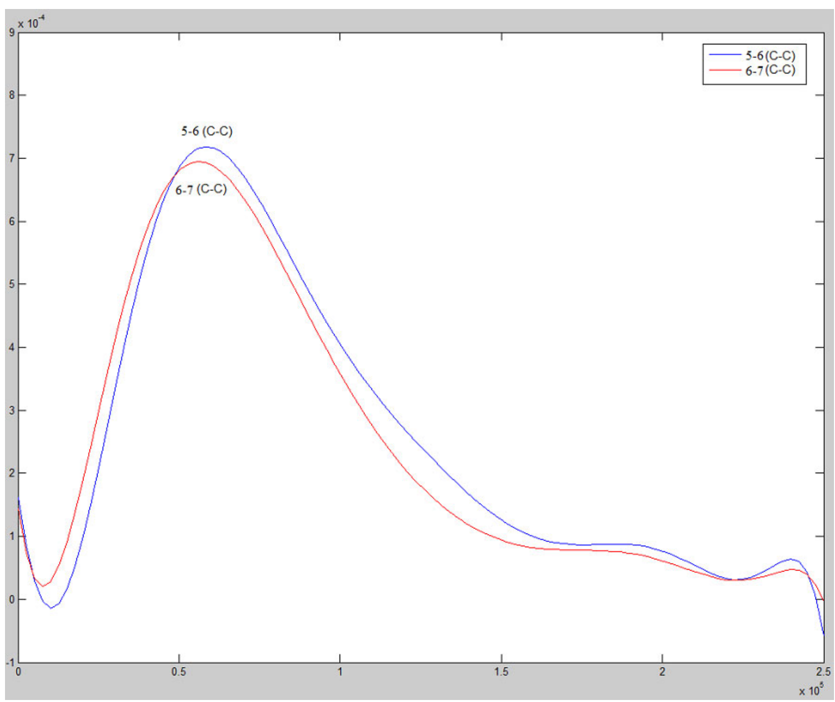


Figure 4. De-noised and Fitted Frequency Domain Curve (5-6 and 6-7)

RESULTS AND ANALYSIS

A three-dimensional tomographic image helps to better evaluate the extent of local defects. Tomography is a mathematical procedure that operates on the measured data where the shaft is modeled as a grid member with each node point assigned as one property of the wave. Existing CSL tomographic methods are based on wave speed, which is based on the change in the FAT since the distance between the CSL tubes is known. This study used a new approach of converting the FTA data to frequency data in the tomography method using the FFT of the signal. Each point in the drilled shaft grid is assigned signal frequency amplitude in the FTA method in order to more accurately locate the defect.

The amplitudes of the signals in time and frequency domains were compared to determine which can better identify the void location. Figures 5 and 6 show the result of the test between the inside tubes 5 and 7 in Specimen 1. Figure 5 is time domain tomography and it shows the amplitude of the signal at different points in time. The horizontal axis indicates the length of the shaft, the vertical axis is data points, and the third dimension shown by color indicates the amplitude or voltage of the signal. Low wave speed or FAT indicates concrete with poor quality. It can be seen that the range of signal strength of the signal from 6 volts in areas of uniform concrete, to -8 volts in areas of defects makes the defect location identification a difficult task.

Figure 6 is the frequency domain tomography. In this figure, the horizontal axis indicates the frequency of the signal, the vertical axis is length of the shaft and the third dimension—shown by color contours—indicates the frequency amplitude of the signal. This plot shows the amplitude of the signal at different points in frequency; low frequency amplitude indicates the location of the void. It can be seen that for areas of normal concrete, the frequency amplitude is around 16×10^{-4}, and this number around the void drops to 10^{-4}. It can be seen that the exact location of the void can be identified using frequency tomography. The major defects in the shaft were at the depth where the frequency amplitude of the signal decreased significantly.

Figures 7 and 8 show the result of the tests between inside tubes 6 and 8 in Specimen 2. Figure 7 shows the time domain tomography and Figure 8 shows the frequency tomography. It can be seen that using frequency tomography, the exact location and size of the defect, while the time domain does not.

CONCLUSIONS AND RECOMMENDATIONS

A method is developed for accurately determining the location of defects in drilled shafts. This method overcomes the limitations and inaccuracies of currently used methods, which rely on the arrival time and wave speed to detect the defects in drilled shaft foundation. The new method is based on a color change in the frequency amplitude of the signal recorded by the receiver probe at the location of defects, and it is named Frequency Tomography Analysis (FTA). The technique has a very good resolution and accurately shows the exact depth location and size of any defect through the length of the drilled shaft. This provides engineers with a technique to improve quality control on the jobsite and to assess the adequacy of the drilled shaft to resist the applied load. Further investigation is recommended in order to study the effect of the vertical alignment of the outside tubes on the accuracy of this method.

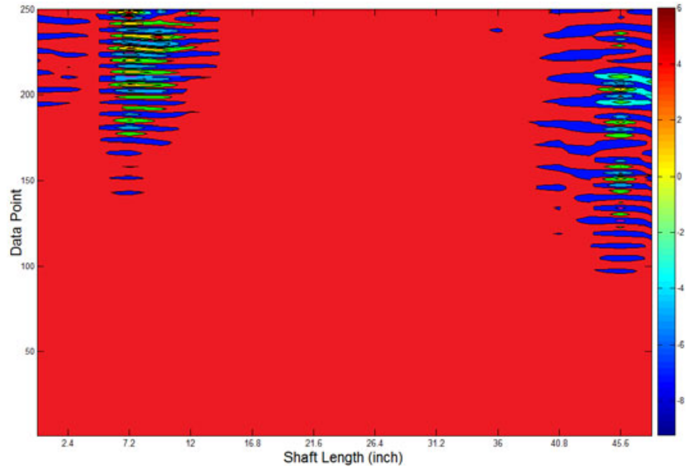


Figure 5. Time Domain Tomography (Specimen 1)

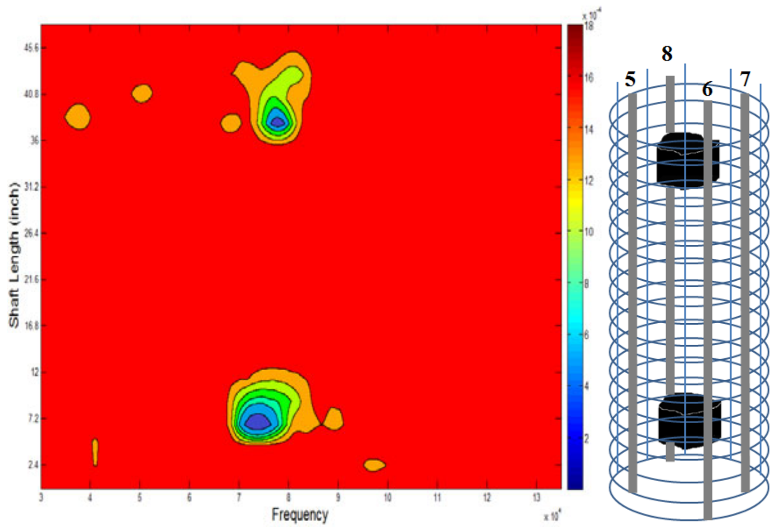


Figure 6. Frequency Domain Tomography (Specimen 1)

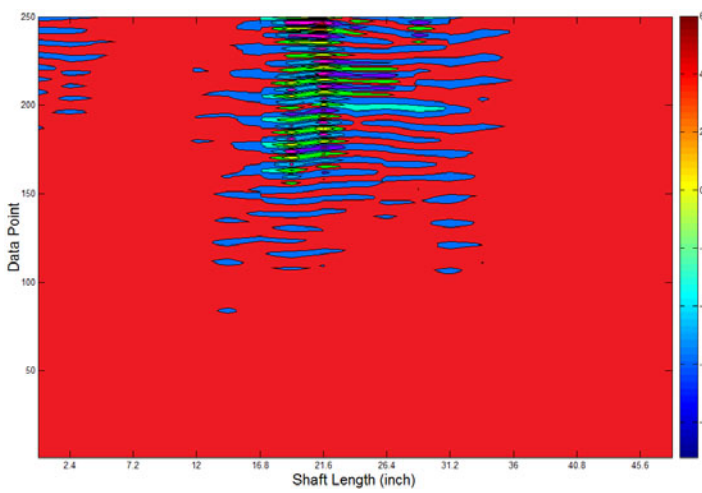


Figure 7. Time Domain Tomography (Specimen 2)

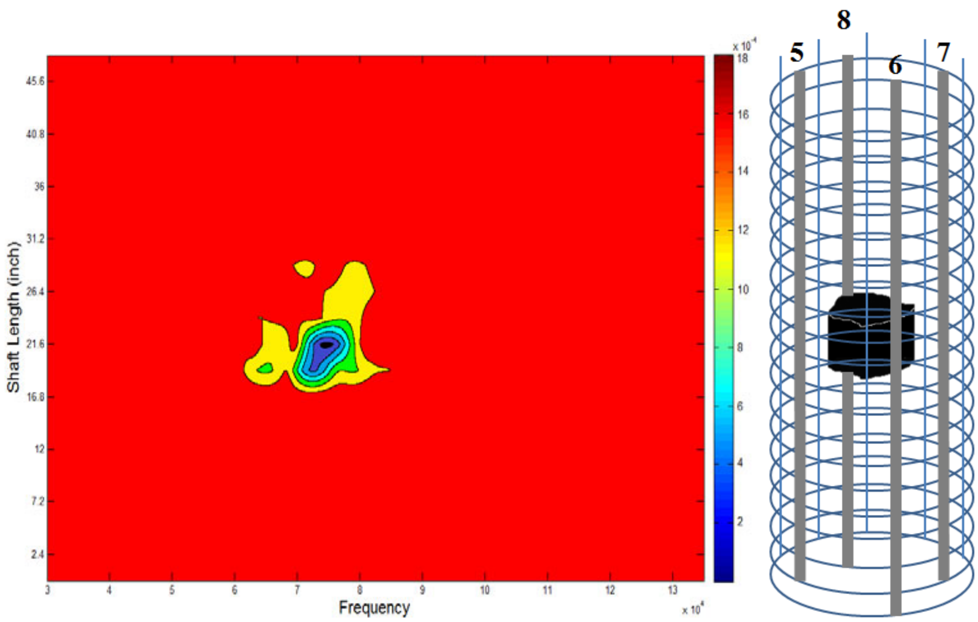


Figure 8. Frequency Domain Tomography (Specimen 2)

REFERENCES

ASTM D6760, (2008). Standard Test Method for Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing.

Baker, C.N., Drumright, E.E., Briaud, J-L., and Mensah, F., (1993). Drilled Shafts for Bridge Foundations. FHWA Publication FHWA-RD-92-004, Federal Highway Administration Office of Engineering and Highway Operations, McLean VA.

Camp, W. M., Holley, D.W., Canivan, G.J., (2007). Crosshole Sonic Logging of South Carolina Drilled Shafts: A Five Year Summary. Deep Foundations, American Society of Civil Engineers, pp. 1-11.

Chang N., Nghiem H., (2008). Drilled Shaft Axial Capacity Due to Anomalies. Report No. FHWA-CFL/TD-08-008. Federal Highway Administration Colorado.

Fullagar, P.K., Livelybrooks, D.W., Zhang, P., Calvert, A.J., Wu, Y., (2000). Radio tomography and borehole radar delineation of the McConnel nickel sulfide deposit, Sudbury, Ontario, Canada Geophysics. 65, pp. 920–1930.

Iskander, M., Roy, D., Kelley, S., and Ea, C., (2003). Drilled Shaft Defects: Detection, and Effects on Capacity in Varved Clay. 10.1061/ASCE,1090-0241, 129:12,1128

O'Neill, M. W., Tabsh, S. W., and Sarhan, H. A. (2003). Response of drilled shafts with minor flaws to axial and lateral loads. Engineering Structures, 25(1), 47-56.

Olson, D. L., Hollema, D. A., (2002). Crosshole Sonic Logging and Tomographic Velocity Imaging of a New Drilled Shaft Bridge Foundation. Structural Materials Technology Topical Conference, Cincinnati, Ohio.

Reese, L. C., O'Neill, M. W., (1999). Drilled Shafts: Construction Procedures and Design Methods. Publication No. FHWA-IF-99-025, Federal Highway Administration.