# The Use of Crosshole Tomography to Evaluate Drilled Shaft Repairs

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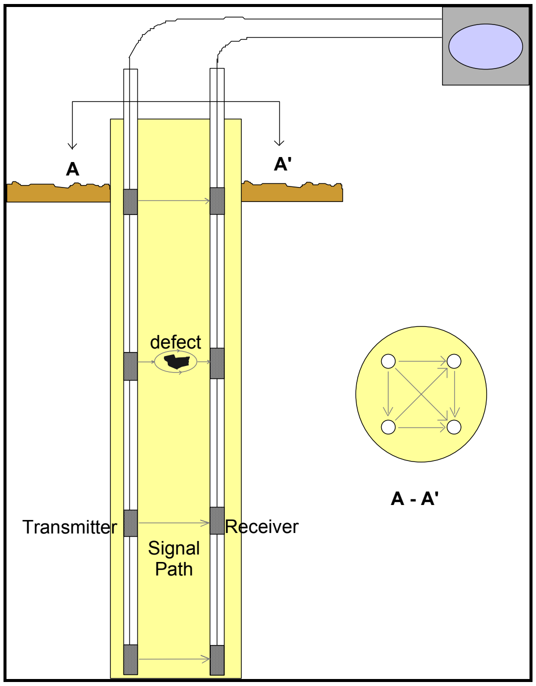
## ABSTRACT

Occasionally, a drilled shaft contains a defect that will significantly affect its performance under design loading and therefore requires remediation. These defects are commonly identified via crosshole sonic logging (CSL) and crosshole tomography (CT) testing techniques and verified via coring. CSL and CT testing can also define the extent and location of the defective zone, which assists in the development of the remediation procedure. In addition to identifying and quantifying defective zones, CSL and CT testing can be used to evaluate the quality of the completed repair. When used in conjunction with repair documentation and materials testing, comparison of CSL and CT testing conducted before and after the repair allows for both qualitative and quantitative assessment of the remediation. The following paper presents several case histories in which CSL/CT testing was effectively used in evaluating drilled shaft defect repairs.

## INTRODUCTION

Drilled shafts are becoming increasingly more common for supporting bridge and building foundations. Since drilled shaft foundations usually carry very high design loads, and often serve as non-redundant, single load-carrying units, there is a need for a high-level of quality assurance and control of the as-built unit. One such method is crosshole sonic logging (CSL) testing, in which ultrasonic signals sent across the drilled shaft concrete are used to assess concrete quality. Ultrasonic signals are sent and received across the drilled shaft from instrumentation lowered and raised in access tubes. These access tubes are attached to steel reinforcement prior to concrete placement. As the ultrasonic transmitter and receiver are simultaneously raised, the ultrasonic signals are recorded. Concrete quality is assessed by examining the First Arrival Time (FAT) and relative energy of the signal along the shaft length. If the distance between the access tubes is known, an apparent signal velocity (i.e. wavespeed of the ultrasonic signal through the concrete) can be determined. Figure 1 presents a typical CSL testing setup while Figure 2 presents typical CSL testing results. CSL testing is described in detail by Chernauskas and Paikowsky (1999).



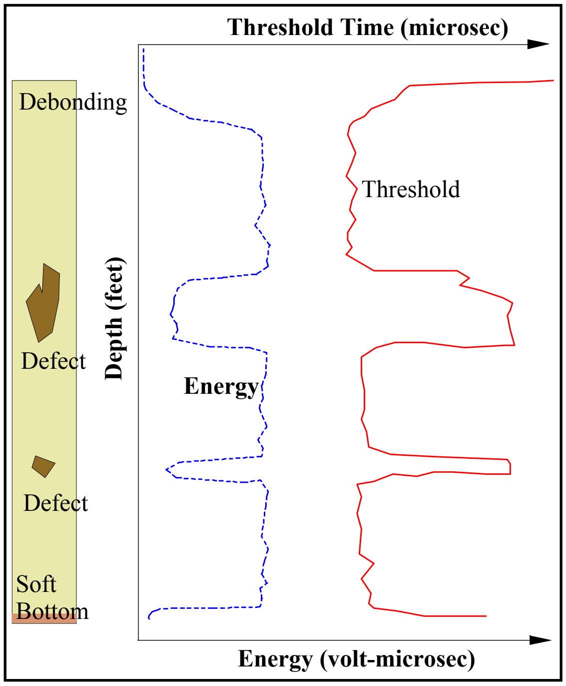
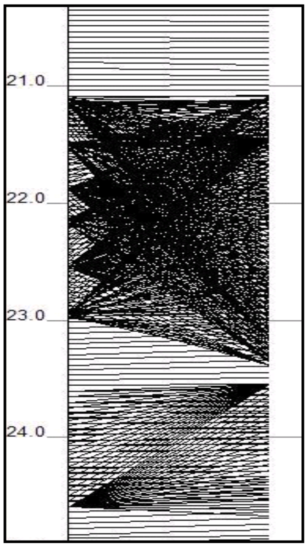


**Figure 1.** Typical CSL Setup. **Figure 2.** Typical CSL Results
(after Chernauskas and Paikowsky, 1999).

A variation on CSL testing is Crosshole Tomography (CT), which represents the condition of the concrete in a graphical manner. While CSL testing consists of simultaneous pulling the ultrasonic transmitter and receiver together through the access tubes, CT testing consists of raising and lowering the ultrasonic transducers so that data is collected at numerous angles through the anomalous zone. Figure 3 graphically presents the data collection procedure for CT testing. Two-dimensional (2D) or three-dimensional (3D) tomography can be performed. Tomographic analysis uses the cross-hole sonic logging (CSL) first arrival time (FAT) data that is converted to velocity based on the distance between the transducers. The signal energy (or attenuation) can also be used in tomography; however, most algorithms are based on velocity. Figure 4 presents typical 2D and 3D CT results. In Figure 4, lower velocities are represented by red and blue areas, while higher velocities are represented by green and gray areas. Simple tomographic techniques use linear wave propagation, while the more complex tomography techniques also use bent-ray and wave front analysis in an iterative approach. Further information on tomography is provided by Bowen and Dianguang (1992) and Piletest (2008).

The following paper examines two (2) drilled shaft case histories in which defects were detected and evaluated using CSL and CT testing, repairs were made, and the drilled shafts re-evaluated after the repair using CSL/CT testing.



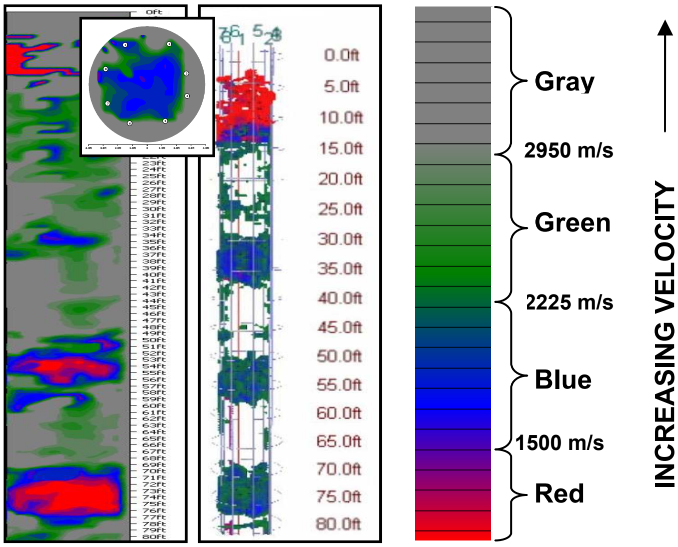


**Figure 3.** Typical CT Test. (After Piletest.com, 2008)

**Figure 4**. Typical 2D & 3D CT Test Results. (key to the right represents velocity shading)

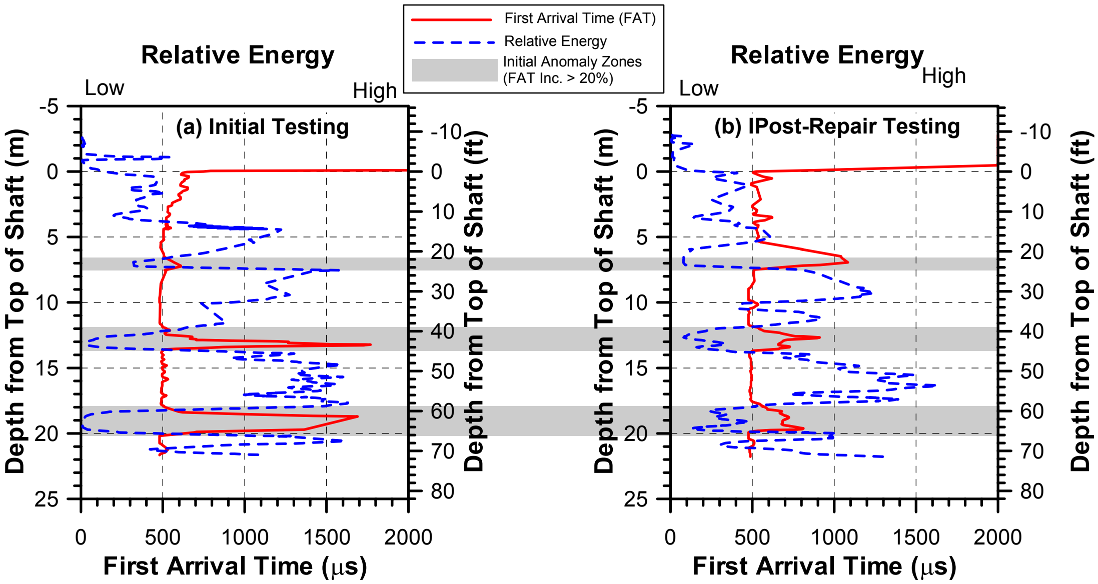
## CASE HISTORIES

Case History 1 (Tremie Pipe Lost/Concrete Placement Problem)

A 2.4 m diameter shaft was constructed for a pier foundation for a bridge over a river crossing. The drilled shaft was constructed by advancing a permanent steel casing through the overburden soils and into rock to the bottom of the shaft. Concrete was delivered using a pump truck and placed using tremie procedures. During concrete placement, the lower 6m of the tremie pipe separated and was lost in the drilled shaft. After concrete placement was completed, excessive cement paste was noted at the top of the shaft.

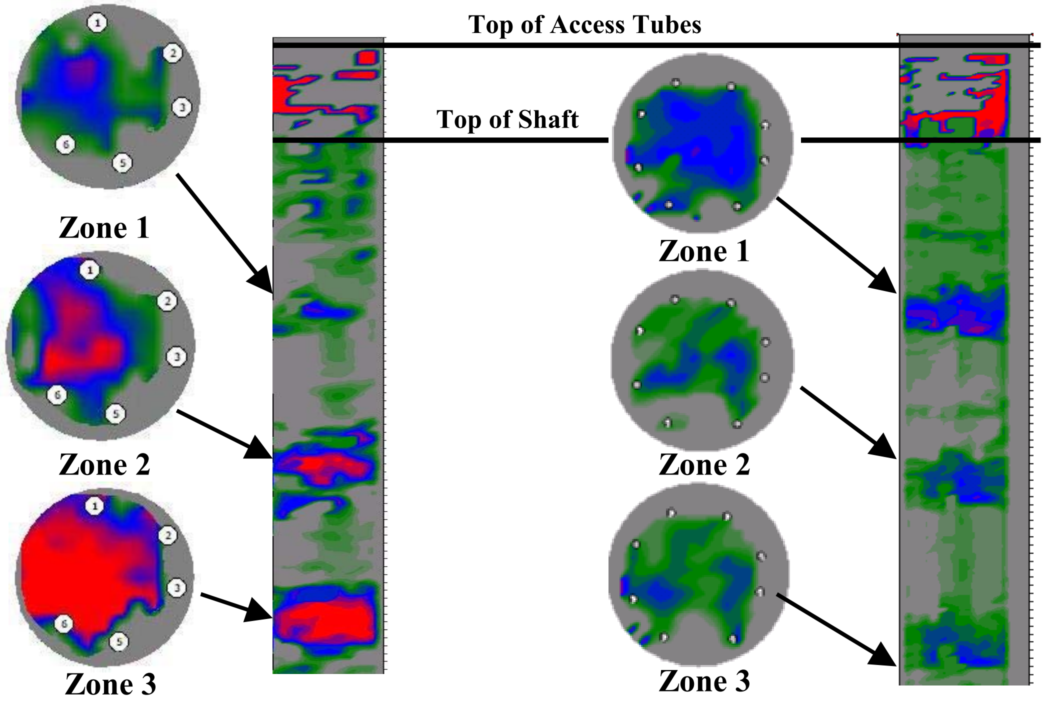
The initial CSL and CT testing performed on the shaft indicated significant anomalies defined by increases in FATs typically greater than 100% and very weak energy levels. Three major anomalous zones, in the shape of "hockey pucks" around 0.9 to 1.8 meters thick, were detected in most tube profiles at approximately 9.8, 15.5, and 21.6 meters below the top of the steel casing. Figures 5a and 6a present the initial CSL testing results (FAT and relative energy) and 2D vertical CT results (apparent velocity), respectively, for a selected access tube combination across the drilled shaft. Figure 6a also presents the initial 2D horizontal (i.e. plan view) CT test results at the three major anomaly zones. As shown in Figure 6a, the upper zone does not appear to contain as much lower strength concrete, as represented by blue and green areas (velocities around 2,300 to 3,000 m/s) compared with the red and blue areas in the middle and lower zones (velocities around 1,500 to 2,300 m/sec).

Four 200 mm diameter core-holes (one in each quadrant of the shaft) were advanced through the anomalous zones to depths of around 24 to 26 meters below the top of the casing. Core samples were obtained and tested for compressive strength between depths of approximately 9 to 26 meters. The cores revealed weaker and segregated concrete in three major zones at depths that correlated well with the anomalous zones identified by



**(a) Initial Testing (Profile 1-5)** **(b) Testing after Repair (Profile 1-5)**

**Figure 5.** CSL Testing Results with Depth for Case History 1.



**(a) Initial Testing (Profile 1-5)** **(b) Testing after Repair (Profile 1-5)**

**Figure 6.** 2D Vertical and Horizontal CT Results for Case History 1.

the CSL/CT testing. The results of the core testing indicated that the concrete compressive strengths typically ranged between approximately 4 and 18.6 MPa in the anomalous zones and between 31 to 44.9 MPa elsewhere.

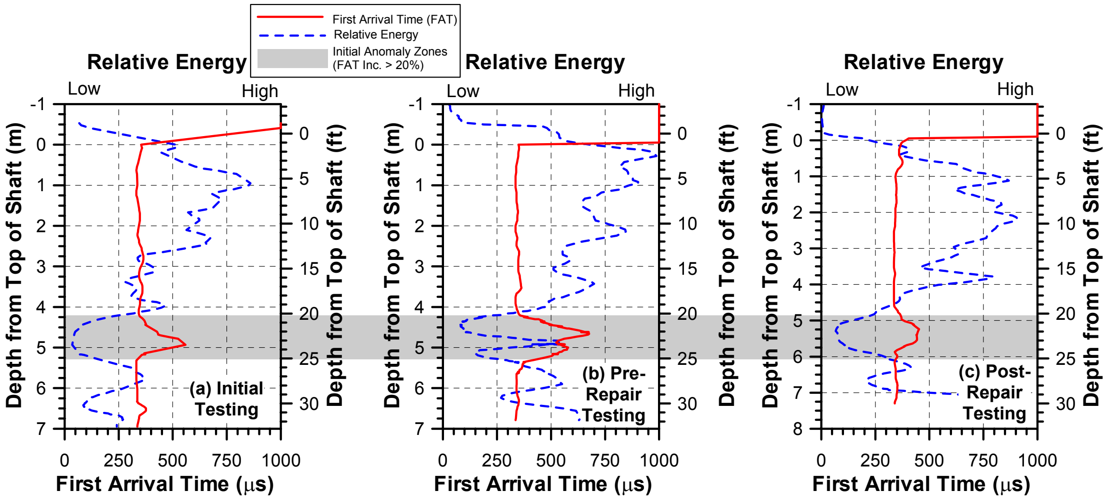
The primary repair procedure involved using a high pressure head to blast out concrete in the three defective zones. Nozzle pressures upwards of 140 MPa were used to cut away and flush out the defective concrete. Remote inspection using a video camera was then performed after flushing and pumping of the zone to visually observe the repair process, which showed almost complete removal of the defective concrete. The zones were then filled with 40 MPa neat cement grout. This procedure was repeated for each zone starting from the lower zone to the upper zone.

CSL and CT testing was performed four (4) days after the completion of the repair of the last (i.e. upper) zone. The post-repair CSL and CT results are shown next to the initial testing results in Figures 5b and 6b, respectively. As shown in Figures 5 and 6, improvements (i.e. decreases in FAT, increases in apparent velocities and relative energy) were observed in the lower two anomaly zones. The velocities in the lower two anomaly zones typically increased to around 2,500 to 3,000 m/sec. The upper post-repair zone indicates a slightly thicker zone with lower velocities than those determined during the initial testing. The greater thickness of the upper zone is most likely a result of the high pressure cutting procedure used to remove the concrete, where additional "good quality" concrete may have been removed at the upper and lower boundaries. The higher FAT increases and lower velocities in the upper zone are most likely due to the shorter grout curing time of approximately 4 days as compared to several weeks for the lower zones. The compressive strengths determined from the post repair core samples indicated grout compressive strengths around 27.6 MPa after 7 to 10 days and over 34.5 MPa after 14 days. Based on the CSL/CT results in conjunction with QC/QA testing of the grout materials, the drilled shaft repair was considered to be successful.

## Case History 2 (Temporary Casing Removal/Tremie Seal Concrete Problem)

A 1.98 m diameter shaft was constructed for a pier foundation for a viaduct. Temporary steel casing was advanced to the top of rock. A 1.3 m diameter rock auger was then used to excavate to the bottom of the rock socket (5.4 m in length). Concrete was then placed inside the shaft excavation to approximately ¼ of the way up the temporary casing using a tremie pipe. The temporary casing was then partially removed using a vibratory hammer. Concrete continued to be placed inside the temporary casing using the tremie pipe in the remaining portion of the excavation. During concrete placement, the tremie pipe became plugged, was pulled out of the concrete, and then reinserted within the concrete. The temporary casing was removed after placement of the concrete to approximately the ground surface elevation.

The initial CSL/CT testing indicated a significant anomalous zone approximately 9 to 10 meters below the top of tubes (4.9 to 5.9 m below top of concrete), defined by increases in FATs typically from 15% to 25% and associated reductions in relative energy. The FAT increases correlated to reductions in apparent velocity of ~20% or more from the nominal value in the non-anomaly zones. Increases in FATs from 40% to 50%, with associated large reductions in energy were observed in tube combinations within the southwestern portion of the socket (tube 1 is north). The FAT increases correlated to reductions in apparent velocity of ~30-35% or more from the nominal value in the non-anomaly zones. Figures 7a and 8a present the initial CSL and CT testing with depth, respectively. Figure 8a also presents the horizontal tomographic slice through the anomaly zone.

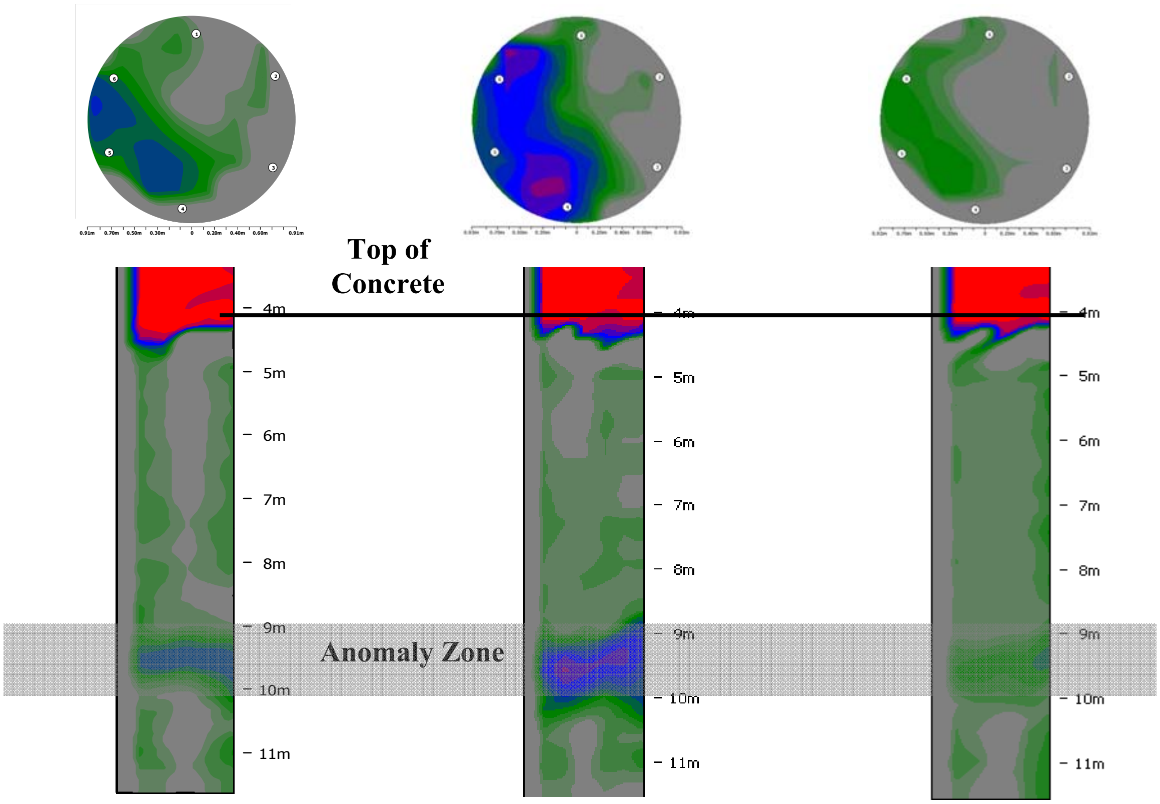


**(a) Initial Testing** **(b) after Flushing/Prior to Grout** **(c) After Repair**

**Figure 7.** CSL Testing Results with Depth for Case History 2 (Profile 2-6).

Three access core-holes were advanced to depths of around 5.2 to 5.7 meters below the top of the concrete. The locations of the holes were selected to provide access and adequate coverage for removal of the suspect concrete based on the CT results. The cores revealed weaker and segregated concrete in the anomalous zone. The concrete compressive strengths typically ranged from approximately 7 to 21 MPa between approximately 4.7 and 5.5 meters below the top of concrete and over 35 MPa above the defective zone. At around 5.5 meters, the material primarily consisted of weakly cemented segregated aggregate that prevented further advancement of the core holes and retrieval of core samples (i.e. the core barrel consistently jammed at this depth at the bottom of the defective zone).

The repair procedure involved using a high pressure nozzle to blast out concrete in the defective zone from the three access holes. Nozzle pressures upwards of 70 to 105 MPa were used to cut away the defective concrete at the top and below the suspect zone. Lower pressures were used to remove the sand/aggregate material in the middle to bottom of the defective zone. Remote inspection using a video camera was then performed after flushing and pumping of the zone to visually observe the repair process, showing that significant removal of the defective concrete was achieved leaving higher quality concrete in-place. After the flushing process was completed and prior to grouting, CSL/CT testing was performed again to characterize and define the water filled flushed out zone (see Figures 8b and 9b, respectively). The CSL/CT results at this stage indicated that the poor material was removed and the remaining void was filled primarily with water (wave speed around 1,500 to 2,000 m/s represented by red & blue areas).



**(a) Initial Testing** **(b) after Flushing/Prior to Grout** **(c) After Repair**

**Figure 8.** 2D Vertical and Horizontal CT Results for Case History 2 (Profile 2-6).

The flushed out zone was then filled with 28 MPa neat cement grout. The grout was delivered under pressure using packers inserted and sealed off within two core holes. The grout was pumped until consistent return was observed flowing through the third open core hole. The 7-day grout compressive strengths ranged between 29 and 32 MPa. CSL/CT testing was performed three days after grouting for use as a comparison with the initial and pre-grouting CSL/CT test results. CSL and CT results for the post repair testing are presented in Figures 8c and 9c, respectively. As shown in Figures 8 and 9, improvements with respect to velocity and relative energy were observed in the repaired zone between initial and post-repair testing. The primary velocity in the post-repair grouted zone was around 3,000 m/sec compared to the typical value of 3,800 m/sec for the concrete above and below the repair zone. The 7-day grout compressive strengths were approximately 30 MPa. Based on the CSL/CT results in conjunction with QC/QA testing of the grout materials, the drilled shaft repair was considered to be successful.

## CONCLUSIONS

CSL testing is a well established tool for identifying anomalous zones in drilled shaft concrete. CT testing can be used to further delineate these zones and aid in developing an investigation plan and repair procedure. As shown in the two (2) presented case histories, CSL and CT testing can also be successfully used to assess drilled shaft repairs compared with the surrounding "good" concrete signals and when considering various repair stages.

As shown in the case histories, apparent velocity ranges within the post repair grouted zones can be lower than the typical values of surrounding "sound" concrete, even when the repair grout 28-day compressive strength of the grout was approximately the same as the "sound" concrete. In addition to curing times, another primary reason for the lower grout velocities is due to the absence of large aggregate in the grout. As a result, under elastic loading conditions, the cement paste (grout) experiences higher strain for a given stress compared with concrete (Neville, 1996). Furthermore, there is no unique relationship between ultrasonic pulse velocity and compressive strength (Sturrup, et. al., 1982 and Popovics, 2001). For example, Sturrup et al. (2982) has shown that the ultrasonic pulse velocity for mortar can be 15 to 20% lower than concrete and for cement paste can be 25 to 30% lower than concrete when the compressive strengths were determined to be the same. Therefore, velocities determined from CT testing for grouted repair zones can in some cases be expected to be somewhat lower than concrete of the same strength. In using CSL/CT testing to evaluate repairs, FAT decreases (i.e. velocity increases) and energy increases and their relative changes compared to surrounding "sound" concrete should be considered in the repair evaluation process more than matching apparent velocities alone.

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