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Edward L. Hajduk
WPC, Mt. Pleasant, South Carolina

Marvin R. Tallent
Palmetto Bridge Constructors, Charleston, South Carolina

Donovan L. Ledford
WPC, Mt. Pleasant, South Carolina

William R. Christopher
WPC, Mt. Pleasant, South Carolina

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CROSSHOLE SONIC LOGGING INTEGRITY TESTING FOR THE NEW COOPER RIVER BRIDGE

Edward L. Hajduk, P.E.
WPC
Mt Pleasant, SC (USA)

Marvin R. Tallent
Palmetto Bridge Constructors
Charleston, SC (USA)

Donovan L. Ledford, P.E.
WPC
Mt. Pleasant, SC (USA)

William R. Christopher, P.E.
WPC
Mt Pleasant, SC (USA)

ABSTRACT

A new cable-stayed bridge for US Highway 17 is currently under construction over the Cooper River between Mount Pleasant and Charleston, South Carolina. This new bridge will replace two existing structures, the Silas Pearlman and the Grace Memorial Bridges. When completed, the new bridge will have a 1,546 feet span over the Cooper River, making this bridge the longest cable-stayed span in North America. The foundations for this replacement bridge are drilled shafts embedded within the Cooper Marl formation, which underlies the near surface lower coastal plain soil deposits. Depending on the location within the bridge structure, the drilled shafts range from 1.07m (3.5ft) to 3.66m (12ft) in diameter with embedments of up to 56.4m (185ft) within the Cooper Marl. The deepest drilled shafts extend to depths of 71.3m (234ft) from mean sea level (MSL).

A total of 410 drilled shafts will be used as the foundations for the new bridge. At of the time of submittal of this publication, a total of 384 of these drilled shafts were installed over a time period ranging from March 2002 to September 2003. The design of the bridge left little redundancy in the drilled shaft foundations. Therefore, integrity testing of the drilled shafts, especially at critical areas such as the main bridge piers, was of major importance to verify that these foundations were capable of supporting the bridge superstructure. Crosshole Sonic Logging (CSL) was selected as the primary testing method to evaluate drilled shaft integrity. This paper presents the results of the drilled shaft CSL integrity testing and discusses the findings of the testing and lessons learned over the course of drilled shaft installation.

INTRODUCTION

Due to the increasing growth of the Charleston, South Carolina metropolitan area and the functional obsolescence of the two existing bridges, a new bridge was designed to span the Cooper River for US Highway 17. This new bridge, named the Arthur Ravenel Bridge, will be the largest cable-stayed bridge in North America when completed. The cable stayed span hangs from two diamond towers at each end of the 1,546 foot span. These towers will be ~575 feet high and support a road deck almost 200 feet above the median high tide mark (SCDOT, 2003). In addition to the replacement bridge, a new interchange between US Route 17 and Interstate I-26, comprised of elevated roadway and new or expanded on/off ramps for these two highways, are also being built. Figure 1 presents a plan view of the entire project.

The new Cooper River Bridge is a design-build project being constructed by Palmetto Bridge Constructors (PBC) of Charleston, SC in conjunction with the designer, Parsons Brinkerhoff of New York, NY. The drilled shafts were constructed by Case Atlantic Company of Clearwater, Florida and PBC. Drilled shaft inspection and crosshole sonic logging (CSL) testing were provided by WPC Engineering and Construction Services, Inc. of Mt. Pleasant, SC.

Due to the high structural loads of the bridge, along with interchange design and cost considerations, drilled shafts were selected as the deep foundation system for the project. The drilled shafts for this project were founded within the Cooper Marl formation. The Cooper Marl is an overconsolidated, fine grained, impure calcareous marine deposit that is typically classified according to the United Soil Classification System as a low plasticity sandy silt (ML) or sandy clay (CL), although it can be classified as MH, CH, or SC. Depth to the Cooper Marl Formation varies from approximately 12m to 30m (~40 to 100 feet) within the downtown Charleston area. Due to the soft clays and/or loose sands that overly the Cooper Marl Formation, most deep foundations within the Charleston area are founded within the Cooper Marl. Refer to Klecan at al. (2001) for additional details concerning the Cooper Marl Formation.

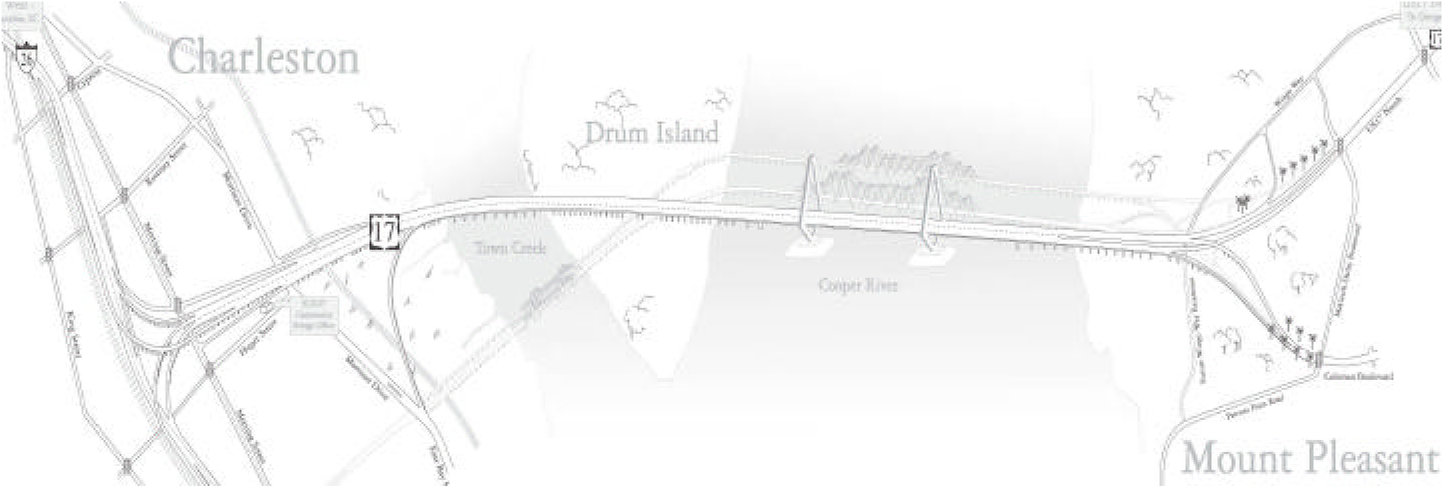

Fig. 1. New Cooper River Bridge Layout (SCDOT 2003).

A total of 410 drilled shafts are to be installed as the foundations for the new bridge and elevated roadways. Shaft diameters within the Cooper Marl ranged from 1.07m (3.5ft) to 3.66m (12ft), with embedment depths into the Cooper Marl Formation ranging from 15.2m (50ft) to 56.4m (185ft). An extensive load test program was conducted prior to the start of the design/build construction process to determine the design parameters for the drilled shafts. Refer to Camp et al. (2002A and 2002B) and Brown and Camp (2002) for details of this load testing program.

The drilled shafts were constructed via "dry" and "wet" construction methods. In the "wet" method, water from the Cooper River was in the shaft during excavation and concrete placement. These shafts are therefore also referred to as water shafts. As concrete was placed within the shaft via a tremie pipe, the water within the shaft was displaced and flowed back into the Cooper River. Proper use of a tremie pipe allowed the placement of concrete underwater without detrimental effects. In the dry method, the shaft excavation was left open during soil removal and concrete placement. These shafts are therefore also referred to as land shafts. A tremie pipe was also used during concrete placement of the "dry" shafts in order to minimize or prevent segregation of the concrete. In general, "wet" methods were used on drilled shafts at offshore locations (i.e. with standing water at low tide) while shafts on land and marsh locations were constructed using the "dry" method.

DRILLED SHAFT QUALITY CONTROL

The design of the bridge left little to no redundancy in the drilled shaft foundations. Therefore, quality control of the drilled shafts during installation was a critical part of the construction process. The drilled shaft quality control started with drilled shaft inspectors, who inspected and completed installation logs detailing all aspects of the drilled shaft construction (e.g. drilled shaft excavation, reinforcing steel placement, and concrete placement). The drilled shaft installation logs were then reviewed by registered SC professional engineers familiar with the drilled shaft construction process and local geotechnical engineering conditions to determine if any irregularities were encountered during the shaft construction. For "wet" shafts, a mini-Shaft Inspection Device (mini-SID) was used to inspect the shaft tip prior to concrete placement. Finally, Crosshole Sonic Logging (CSL) tests were conducted on selected and random shafts to evaluate shaft integrity.

CROSSHOLE SONIC LOGGING TESTING OVERIEW

Crosshole Sonic Logging (CSL), a.k.a. sonic coring, is used to evaluate the condition of the concrete within cast-in-place deep foundations such as caissons or drilled shafts (Chernauskas and Paikowsky, 1999). CSL testing involves placing a transmitter and receiver down pre-installed access tubes in various combinations across the shaft. As the gages are pulled up the shaft, ultrasonic pulses are sent across the shaft and recorded at set intervals by a data acquisition system. A typical source/receiver arrangement for a drilled shaft is shown in Fig. 2. Changes in the arrival time (i.e. threshold) values and/or reductions in signal energy are indicative of anomalies within the concrete. Chernauskas and Paikowsky (1999) provide a detailed description of CSL testing.

The CSL testing of the drilled shafts for this project was conducted in accordance with ASTM Standard D6760-02 *"Standard Test Method for Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing."* The CSL testing was performed using the CrossHole Ultrasonic Module (CHUM) of the Pile Integrity Sonic Analyzer (PISA) system. The PISA is a lightweight, portable, pen touch computer that operates in a Windows based environment (Chernauskas and Paikowsky, 2000). The PISA has been shown to detect known/confirmed defects within deep foundation systems (Chernauskas and Paikowsky, 2000, Haramy and Mekic-Stall, 2000, and Amir, 2002).

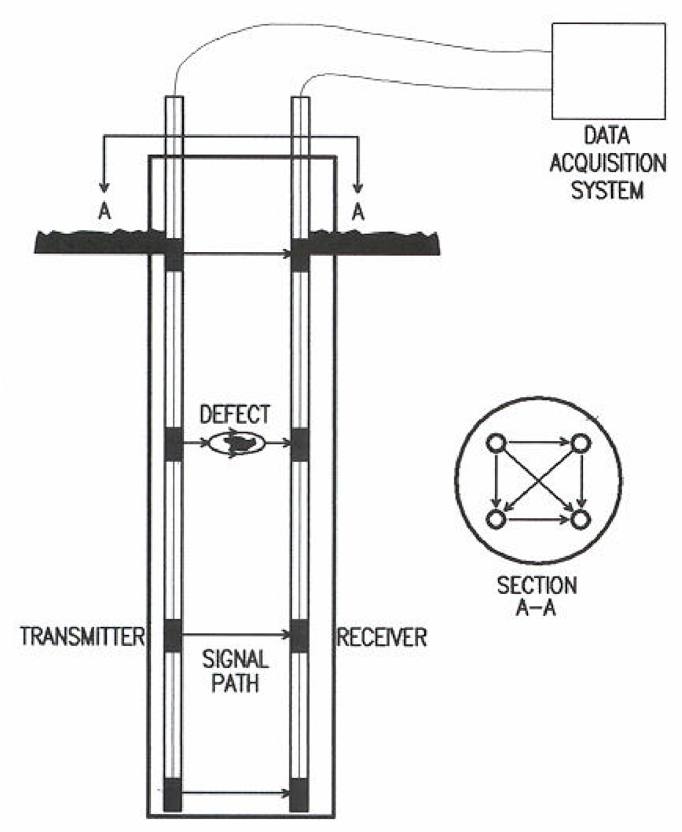

Fig. 2. Typical CSL setup (after Chernauskas and Paikowsky (1999).

The project specifications regarding drilled shaft CSL testing specified the following:

- The CSL access tubes were to be comprised of 5.1 cm (2 inch) Schedule 40 steel piping.
- The CSL access tubes were to be within 15.2cm ± 7.6cm (6inches ± 3inches) of the shaft tip and extend a minimum of 7.6cm (3inches) from the shaft top.
- Initial CSL testing was to be conducted between three (3) to ten (10) days after placement of concrete and after the concrete had reached a compressive strength of 20.7MN (3,000 psi).
- Initial CSL testing was to be comprised of testing the perimeter and major principal diameter combinations. An example of the required access tube combinations for initial CSL testing for an eight access tube shaft is shown in Figure 3.
- CSL testing was to be conducted at a minimum of 64 mm (2.5 inch) intervals along the shaft length.
- For CSL re-tests, all possible access tube combinations were to be tested.

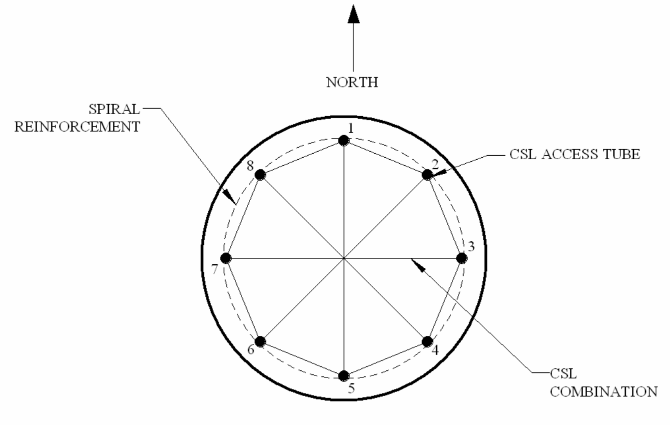

Fig. 3. Typical Drilled Shaft Layout – Eight (8) Access Tubes.

To maintain consistency of access tube numbering throughout the project, the northern access tube for each drilled shaft was designated as access tube 1. The remaining access tubes were numbered sequentially heading clockwise around the drilled shaft. Figure 3 shows a typical CSL access tube numbering layout for an eight access tube shaft.

Although the project specifications called for steel access tubing, several shafts had 3.8cm (1½ inch) nominal diameter Schedule 40 PVC access tubing at the upper 5 ft of the shaft. Due to the confined space at the shaft top from the large quantities of steel reinforcement required, 5.1 cm (2 inch) Schedule 40 steel pipe could not be used at the shaft top for several drilled shafts. Therefore, after consulting with the designer, lower diameter PVC access tubing was used. A total of 28 tested drilled shafts had PVC access tubing at the shaft top.

The CSL signal spacing was refined by the CSL testing engineers to the spacing presented in Table 1. This refinement of the signal spacing accounted for shaft length and type of test (i.e. CSL re-testing) and would allow for refined anomaly definition.

Table 1. CSL Signal Spacing Summary

Condition	**CSL Signal Interval**
Shaft Length = 30.5m (100ft)	2.5cm (1in.)
Shaft Length > 30.5m (100ft)	5.0 cm (2in.)
All CSL Re-tests	2.5cm (1in.)

The initial quality control plan for the drilled shafts called for CSL testing to be conducted on a minimum of 50% of the drilled shafts with the following selection breakdown:

- 25% of the drilled shafts were selected by the South Carolina Department of Transportation (SCDOT). These included the drilled shafts at critical areas such as the main bridge piers.
- An additional 25% were selected at random as part of the contractor's quality control program.
- Drilled shafts that did not meet project construction specifications and/or encountered unusual conditions/activities during shaft construction were selected for CSL testing.

CSL Anomaly Definition

Anomalies in CSL testing are defined as areas that experience an increase in the First Arrival Time (FAT) and/or a reduction in relative energy of the ultrasonic signal. Changes in relative energy can sometimes indicate defects based on the degree of reduction and the associated FAT increase. For this project, the FAT increases presented in Table 2 were selected as a general guideline for CSL anomaly definition.

Table 2. General CSL Anomaly Definition based on FAT.

FAT INCREASE	REMARKS
0 to 10%	Not significant.
10 to 30%	Possible Anomaly. Requires detailed analysis.
>30%	Anomaly. Requires further evaluation.

After identification of possible anomaly areas were made using FAT's, anomaly areas were further investigated using apparent wavespeed. Apparent wavespeed is defined as the distance between the access tubes (as measured at the top of the drilled shaft) divided by the FAT. The Concrete Condition Rating Criteria (CCRC) is currently being used by the Federal Highway Administration (FHWA) and several state Departments of Transportation (DOT's) for assessing concrete quality from CSL results. Table 3 presents a summary of the CCRC.

In addition to the general anomaly definition, terms associated with CSL testing were also clearly defined for the project. After several meetings between the contractor, designer, and CSL inspection firm, it became obvious that different items were being referred to by numerous titles. Therefore, the following definitions for anomaly and defect were established for the project:

- Anomaly: An irregularity or series of irregularities observed in an ultrasonic profile (i.e. CSL results) indicating a possible defect (after ASTM D6760).
- Defect: Any area within the drilled shaft confirmed to be out of specification.

Table 3. CCRC (after CFLHD, 2002).

Rating & Symbol	**Velocity Reduction**	**Indicative Results**
Good (G)	0 to 10%	Acceptable concrete
Questionable (Q)	10%-25%	Minor concrete contamination or intrusion. Questionable quality concrete.
Poor (P/D)	≥25 %	Defects exist, possible water slurry contamination, soil intrusion, and/or poor quality concrete.
Water (W)	1,450 m/s = V = 1,525 m/s	Water intrusion or water filled gravel intrusion with few or no fines present.
No signal (NS)	No signal received	Soil intrusion or other severe defect absorbed the signal, tube debonding if near top.

CSL TESTING RESULTS

Overall Summary

At the time this paper was submitted, a total of 183 of the 384 (48%) drilled shafts installed for the project were evaluated using CSL testing. This number is slightly below the minimum threshold for CSL tested shafts set prior to the start of construction with 28 drilled shafts remaining. A summary of the CSL testing at the time of submittal of this paper is presented in Table 4.

Table 4. CSL Testing Summary.

Drilled Shaft Type/ Construction Method	**Shafts Installed**	**Shafts CSL Tested**	**% CSL Tested**
Total	384	183	48%
”Wet” Method	61	61	100%
“Dry” Method	323	112	35%

Change in CSL Selection Criteria

Over the course of drilled shaft placement and testing, the criteria for selecting drilled shafts for CSL testing was changed for the project. This change in selection criteria was based on the CSL results acquired over the course of testing, which showed the following:

- Land shafts which experienced no unusual construction activities had consistent, quality concrete through the lengths of the shafts.
- A series of tip anomalies at the base of several water shafts.

Based on these results, the criteria for selecting which drilled shafts were to be CSL tested were changed to the following:

- All water drilled shafts were to be CSL tested. A total of 71 water drilled shafts (17% of the total) were planned for this project. During the course of the project, the final 10 water drilled shafts were constructed using the "dry" method in an attempt to eliminate the occurrence of shaft tip CSL anomalies. Therefore, only 61 drilled shafts (15% of the total) were constructed using the "wet" method. All of these shafts were CSL tested.
- 25% of the remaining drilled shafts were selected at random by the contractor.
- Drilled shafts that did not meet project construction specifications, encountered unusual conditions and/or activities during shaft construction, or those individually selected by the SCDOT were CSL tested.

CSL Access Tube Test Program

As previously mentioned, a series of tip anomalies were detected at the base of several of the water drilled shafts. Two possible alternative causes of the CSL anomalies (i.e. causes not indicative of problems within the drilled shaft) were identified: interior and exterior contamination of the access tubing.

Interior contamination might have been caused from rust developing along the tube interior from the water left in the tubes after the CSL testing. This rust may have been vibrated loose during repeated contact with gravel being placed around the pier for the rock island barrier. In addition, fines from the gravel could have also been introduced into the access tubes during rock island placement.

In order to determine if interior contamination was causing the CSL anomalies, three (3) access tubes from a representative drilled shaft were flushed with clean water and CSL re-tested. Analysis of the CSL re-test data detected the anomalies previously observed in the initial CSL testing and the 1st CSL re-test, slightly stronger signal strengths, and an increase in FAT or non-discernable FAT's within some of the anomalies. Based on these observations, interior tube contamination was eliminated as a possible cause of the CSL anomalies.

A review of the drilled shaft installation logs showed that access tube extensions of up to 0.46m (1.5ft) in length were placed at the bottom of the access tubes. Based on conversations with construction personnel and the drilled shaft inspectors, it was determined that these tube extensions were added on the barges prior to placement of the reinforcing cage into the shaft excavation. The tube extensions were comprised of scrap tubing and may have been contaminated with hydraulic oil, grease, and other lubricants while on the barge and/or during splicing onto the existing tubes. Prior CSL testing experience indicated that exterior contamination of the access tubes can prevent bonding between with the concrete, which can prevent the ultrasonic signal used in CSL testing from traveling across the shaft.

In order to determine if exterior contamination common to the working conditions on the barges could produce anomalies similar to those detected during the CSL testing, a CSL access tube test program was developed. This program consisted of placing "clean" and contaminated access tubing into a 3.05m by 2.74m by 0.91m (10ft by 9ft by 3ft) concrete block. The tubes were placed within this block so that a minimum of (6in) of concrete cover was around the tubing. The tubing was comprised of residual pieces of tubing similar to that used from the extensions and were spaced at intervals similar to the distances typically encountered for the perimeter and major diameter combinations tested on the drilled shafts. This interval corresponds to 0.91m (3ft) for the perimeter combinations and 2.67m (8.75ft) for the major diameter combinations. Selected tubes were "contaminated" by using the grease and pipe dope prior to concrete placement. CSL testing personnel were unaware of which tubes were contaminated and conducted a CSL test of the concrete test program 3 days from the placement of concrete.

This testing program showed that the use of grease effectively blocked the CSL signal while "pipe dope" affected several of the CSL signals within the tested perimeter combinations. No signal was detected in any of the major principal diameter combinations. Therefore, no conclusions could be drawn from the major principal diameter testing. However, it is logical to assume that if grease contamination affected the perimeter combinations, then it would affect major diameter combinations as well.

Time of CSL Testing from Concrete Placement

As previously mentioned, the project specifications stated that CSL testing was to be conducted within 3 to 10 days from concrete placement. During CSL testing of the initial large diameter (i.e. 2.4m (8ft) or greater diameter) land shafts, temperatures of in excess of the manufacturer's recommended maximum temperature were observed within the access tube water up to 8 days from the end of testing. As a result, several CSL gages were damaged beyond repair. To avoid future damage to the CSL gages, the following steps were implemented:

- Testing on large land drilled shafts was scheduled after a minimum of 7 days from date of concrete placement.
- Measurements of access tube water temperatures were taken on drilled shafts where the access tube tape weights were "hot" to the touch during access tube depth measurement. CSL testing was re-scheduled for drilled shafts with access tube water temperatures < 130°F, which is safely below the manufacturers' recommended maximum temperature.

Comparison of CSL data from drilled shafts tested within 10 days from concrete placement to CSL test data greater than 10 days from time of concrete placement showed no degradation of ultrasonic signal which would affect the ability of CSL testing to evaluate the integrity of the drilled shaft. The greatest time frame between concrete placement and CSL testing for the project was 314 days. Comparative analysis of the CSL data showed that within similar CSL combinations, the 314 day test results showed the same anomaly regions.

Further analysis of CSL tests for the same drilled shaft conducted at 12, 248, and 314 days from concrete placement showed no significant increases in First Arrival Times (FAT) within non-anomaly regions. Table 5 presents a comparison of FAT differences with time within drilled shaft W16B for two access tube combinations at three separate depths. As shown in Table 5, the FAT differences with time are less than 7% and average ~4%.

Table 5. Comparison of FAT differences over Time for drilled shaft W16B.

Combination	**Height[1] (ft)**	**Δ FAT[2] (%)**	
		248 Days from CP[3]	**314 Days From CP[3]**
26	20	-5.9	-4.9
	80	-3.9	-4.2
	150	-3.9	-6.9
48	20	-5.4	-3.0
	80	-3.4	-4.4
	150	-1.3	0.5

NOTES:

1. Height from Bottom Of Access Tubes (BOAT).
2. Δ FAT = FAT difference from initial CSL testing at 12 days from concrete placement.
3. CP = Concrete Placement

Although the CSL testing during the course of the project showed that CSL testing could effectively evaluate drilled shaft integrity beyond 15 days, every effort was made to complete the CSL testing within the project specification time window.

Access Tube Debonding

Access tube debonding is the separation of the access tube from the surrounding concrete and/or weakening of the interface between the two materials. Typically, access tube debonding occurs when polyvinyl chloride (PVC) pipe is used in place of steel, although debonding can occur when steel tubing is used. As the concrete cures, the heat of hydration causes increased temperatures with the drilled shafts. This increased temperature causes the access tubing to expand. As the concrete cools, the access tubes contract, causing separation between the two materials and/or weakening of the interface bond. If the material thermal expansion properties between the concrete and access tubing are substantially different, the potential for the interface (i.e. bond) between the two materials to be affected is greater. Disturbance of the interface or a separation between the two materials can cause increased FAT times and/or reduced relative energy of the signal.

Over the course of the project, CSL anomalies attributed to access tube debonding were limited to 8 drilled shafts with steel access tubes and 24 drilled shafts with PVC access tubing at the shaft top. Of these drilled shafts, the debonding occurred within zones of concrete at the shaft top slated for removal within 7 of the drilled shafts with steel tubes and therefore was not a cause for concern. The 8th drilled shaft was cored through the debonding zone and visual inspection of concrete samples from this inspection core revealed no irregularities, while compression strength testing confirmed that the compressive strength was above the design value and near the average of the design mix compressive strength test cylinder results.

Debonding of the PVC access tubing located at the shaft top was expected, given the author's previous experience with access tube debonding in South Carolina (Hajduk et al., 2003). Inspection cores conducted on two drilled shafts with PVC access tubing revealed that concrete within the upper debonding zone had no significant visual irregularities and approximately the same compressive strength as the shaft concrete outside the debonding zone. In addition, a review of the installation records for these drilled shafts showed no unusual activities and the construction was within project specifications. These facts, coupled with the size of the debonding zone correlating precisely with the length of PVC pipe, confirmed that these zones could be attributed to debonding.

Inspection Coring

CSL anomalies not attributed to debonding were detected within 22 drilled shafts that were significant enough that further examination via inspection coring was recommended. To further investigate these, a total of 60 inspection/repair cores were conducted within these drilled shafts. The inspection core samples were visually evaluated to determine irregular concrete zones using ACI 201.1 R-92 (Re-approved 1997) *Guide for Making a Condition Survey of Concrete in Service*. Areas with irregular concrete (such as honeycombing) were noted and further examined by several methods, such as petrographic analysis, compressive strength testing, etc. A summary of the inspection coring is provided in Table 5.

Table 5. Inspection Coring Summary.

Item	Quantity
Drilled Shafts in which Inspection Coring was recommended and performed	22 (5% of Total, 12% of CSL tested)
Number of Significant CSL Anomalies within cored Drilled Shafts	32
Number of Significant CSL Anomalies confirmed to have irregular concrete within Inspection Cores	24 (75%)
Number of Inspection Cores	60
Number of Inspection Cores with Irregular Concrete at CSL Anomalies	52 (87%)

As shown in Table 5, 75% of the significant CSL anomalies were confirmed to be areas of irregular concrete that affected the CSL signal. A total of 87% of the inspection cores detected irregular concrete at the CSL anomaly locations. Evaluation of the irregular concrete to determine if the irregular concrete/CSL anomaly areas were defects within the drilled shafts was conducted by the design-build team in conjunction with the CSL testing engineering firm. The details of this evaluation procedure are beyond the scope of this paper and will be addressed in future publications by the authors and the design-build team.

Detailed examination of the drilled shaft installation logs showed that the majority of CSL anomalies could be correlated with unusual construction activities. These activities included removal of the concrete tremie pipe during concrete placement, improper re-insertion of the tremie pipe, and delays in the concrete placement.

CSL Confirmation Testing.

Drilled shafts with defects confirmed by inspection coring were repaired in such a manner that the shaft was able to carry the required structural load. Repair methods were developed by the design-build team on a shaft by shaft basis, but generally consisted of "cleaning" the anomaly area using water under pressure (i.e. hydro-demolition). Non-shrink grout was then placed under pressure within the defect zone. Actual drilled shaft repair details are beyond the scope of this paper and will be addressed in future publications by the design-build team.

CSL testing was performed within the repaired drilled shaft zones to verify the effectiveness of the repair procedure. A total of 8 drilled shafts with repairs were evaluated using CSL testing. Comparisons were made to the previous CSL results to determine the extent and relative concrete strengths within the repaired regions. The results of the CSL testing consistently showed increased FAT and CSL signal energies, indicating successful repairs. Details of CSL repair analysis procedures are beyond the scope of this paper and will be addressed in future publications by the authors.

SUMMARY AND CONCLUSIONS

Of the 384 drilled shafts for the new Cooper River Bridge project constructed at the time of this publication, 183 (48%) were CSL tested. The CSL testing identified 32 anomalies within 22 drilled shafts that were further investigated by inspection coring. This number of drilled shafts is 12% of the drilled shafts with CSL testing and 5% of the total number of drilled shafts. A total of 60 inspection cores were conducted on these 22 drilled shafts. Of the 32 CSL anomalies, 24 (i.e. 75%) were confirmed to be areas of irregular concrete by the inspection cores. In addition, 52 of 60 inspection cores (i.e. 84%) detected irregular concrete at the CSL anomaly locations.

From the presented data, the following conclusions were drawn:

- The CSL testing was effectively used as part of an overall quality control program for the drilled shaft foundations for the new Cooper River Bridge. This was facilitated by the development of a sound relationship between the design/build team and the CSL testing firm, which smoothly incorporated CSL testing into the quality control process for the drilled shafts.

- The results of the CSL testing were used over the course of the project to focus quality control on areas with a higher frequency of anomalies (e.g. water shafts)

- A high rate (75%) of CSL anomalies were confirmed as irregular concrete from the inspection coring. This confirms the effectiveness of CSL testing to evaluate drilled shaft integrity.

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