COST AND TECHNICAL COMPARISON OF NON-DESTRUCTIVE TEST METHODS FOR DRILLED SHAFTS

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ABSTRACT

Quality assurance of drilled shafts is highly dependent upon the construction practices used during the excavation and concrete placement process. When performed under slurry, challenges are presented in maintaining borehole stability and placing a uniform and continuous concrete column. An integral part of the construction operation is to evaluate the as-built integrity to verify the drilled shaft is capable of safely transferring the required loads to the subsurface. One such case is exemplified by a project involving the expansion of an existing public transit rail line. The expansion required the construction of a new bridge bent supported by seven 5-ft diameter drilled shafts of various lengths. The specifications for the project required both Cross-Hole Sonic Logging (CSL) and Thermal Integrity Profiling (TIP) for drilled shaft integrity evaluation. Both of these post-construction non-destructive tests (NDT) are designed to detect anomalies or the presence of regions with reduced concrete quality. However, the implementation and methodologies of performing each of these NDT methods are significantly different. Cross-Hole Sonic Logging uses ultrasonic signals emitted from a transmitter in one access tube to a receiver in another access tube. Thermal Integrity Profiling measures elevated concrete temperatures during the curing process using embedded thermal wires. Both test methods require different access details and therefore have different costs associated to the contractor or owner to perform. This paper provides a detailed comparison of these NDT methods as performed on these seven drilled shafts. The associated financial and time costs to perform each method are compared and the results are discussed in detail.

Keywords: Cross-Hole Sonic Logging, Thermal Integrity Profiling, cost analysis, quality control

INTRODUCTION

Drilled shafts are a fundamental deep foundation element that can be designed to resist large bending moments as well as to transfer large compressive axial loads through weaker upper soils to competent soils or rock below. Often times when the upper soils are very soft, lateral support by casing or slurry, or a combination of both, may be used to hold back the softer soils from collapsing into the hole before concrete has been placed. Due to the blind nature of drilled shaft construction and the qualities issues that may arise during the placement process, it is essential for design engineers to specify non-destructive testing (NDT) to assess the quality of the as-built drilled shaft. CSL and TIP testing are two NDT methods designed to detect areas of lower quality concrete or soil inclusions throughout the length of the drilled shaft and determine its overall quality. Each method uses different technologies and methods to achieve the results required to determine the as-built condition of the drilled shaft.

Both CSL and TIP test methods have unique monetary costs that are specific to each test. CSL testing requires the purchase and installation of access tubes to the reinforcing cage. After the testing is complete, it is generally required that each access tube be post-grouted. TIP testing requires the purchase and installation of Thermal Wire® cables onto the reinforcing cage. Time is another major factor in the construction industry and both CSL and TIP require a specific amount of time after placement before the results of the test can be analyzed. CSL testing requires that the concrete in the drilled shaft has reached sufficient strength in order to transmit the ultra-sonic pulses from the transmitter to the receiver through the concrete as described by Webster, K. (2011). The time specified before a CSL test can be performed ranges from three to seven days after concrete placement. The time required for the concrete to obtain an acceptable strength is highly dependent on the cement content, aggregate, and the combination of admixtures in the concrete mix design. TIP testing also requires time after the concrete placement and for the hydration process between the cement and water to reach the peak temperature before the results can be analyzed. The window for TIP analyses is between the time of half peak temperature and peak temperature. The time required to reach the peak temperature is a function of the diameter of the shaft, cement content, aggregate, and admixtures in the concrete mix. The hydration process reaching peak temperature usually occurs between ten to forty-eight hours after concrete placement, although this time can be longer, especially in cases where retarders are used.

Different agencies have different acceptance criteria for both CSL and TIP that must be satisfied in order to categorize the drilled shaft acceptable. For this project the criterion for CSL testing is based on categories as described by Webster, K. (2011), with the categories of Good and Questionable concrete being acceptable, Poor/Flaw at the discretion of the engineer of record, and Poor/Defect requiring further methods of investigation. The TIP criterion for this project was based on the criteria discussed by Piscsalko, G. (2016) which states that if cover criteria is met and a 0% to 6% effective radius reduction is observed then the shaft is considered Satisfactory (S). If cover criteria is not met or if an effective average radius reduction of greater than 6% of the nominal radius is indicated the shaft is categorized as Anomaly (A) and requires further methods of investigation. During the testing on this project, multiple CSL and TIP analyses showed evidence of the presence of potential anomalies which will be discussed later in this paper.

FINANCIAL COST COMPARISON

CSL and TIP testing both have different requirements and methods for data acquisition. CSL requires multiple steel access tubes be installed along the length of the reinforcing cage and extending a reasonable distance above the top of the shaft. The number of tubes required is equal to the diameter of the shaft in feet. For this project the drilled shafts tested were five-foot diameter shafts that ranged in lengths from 60.8 to 75.6 feet of embedment. CSL tubes are typically purchased in 21 foot sections and spliced together using union couplings, which is included in the cost of the 21 foot section, to achieve the desired length of the reinforcing cage plus the required stick-up to ensure there is enough tube length extending above the top of the drilled shaft to properly run the test. Each tube also requires the installation of a cap on the tube at the base of the drilled shaft. After CSL testing is complete post grouting is generally required to fill the CSL tubes.

Similar to CSL, TIP requires that Thermal Wire® cables be installed along the length of the reinforcing cage. The same standard applies to Thermal Wire® cables as CSL tubes in which the number of cables required is equal to the diameter of the drilled shaft in feet. Table 1 below summarizes the consumables purchased for this project for each drilled shaft in order to perform both CSL and TIP testing.

Table 1. Total Quantities of Consumables Required to Perform CSL and TIP Testing.

Drilled Shaft Identification		Shaft 1	Shaft 2	Shaft 3	Shaft 4	Shaft 5	Shaft 6	Shaft 7
Length of Drilled Shaft	ft.	64.5	69.3	67.9	65.4	60.8	60.9	75.6
Number of 21ft CSL Tube Sections (each section includes coupler)	qty.	20	20	20	20	15	15	20
Number of Caps	qty.	5	5	5	5	5	5	5
Required No. of Thermal Wires	qty.	5	5	5	5	5	5	5
Total Linear Feet of Tube	ft.	420	420	420	420	315	315	420
Total Linear Feet of Cable	ft.	350	350	350	350	350	350	400

To estimate the total cost to the project for the installation of CSL and Thermal Wire® cables, a range of unit rates for this project have been provided for use in this paper. For the purposes of estimating the cost associated to both the consumables and labor to install the required access method the average of the unit rate was used. Table 2 below details the range of reported unit rates, the average unit rate used in the analysis, and associated cost per shaft.

Table 2. Summary of Consumable and Labor Costs Associated to Install CSL Tubes and TIP Cables

	Range of Unit Rate (U.S. Dollars)	Average Unit Rate (U.S. Dollars)	Shaft 1	Shaft 2	Shaft 3	Shaft 4	Shaft 5	Shaft 6	Shaft 7
CSL Tube Cost per LF	$6.00 - $7.00	$ 6.50	$2,730.00	$2,730.00	$2,730.00	$2,730.00	$2,047.50	$2,047.50	$2,730.00
CSL Cap cost	$9.50 - $10.00	$ 9.75	$ 48.75	$ 48.75	$ 48.75	$ 48.75	$ 48.75	$ 48.75	$ 48.75
CSL Install Cost per Tube (Labor)	$135.00 - $145.00	$ 140.00	$ 700.00	$ 700.00	$ 700.00	$ 700.00	$ 700.00	$ 700.00	$ 700.00
CSL Post Grouting per LF	$3.15 - $3.25	$ 3.20	$1,120.00	$1,184.00	$1,180.80	$1,184.00	$1,012.80	$1,011.20	$1,350.40
Total Cost per Shaft for CSL Tube	-	-	**$4,598.75**	**$4,662.75**	**$4,659.55**	**$4,662.75**	**$3,809.05**	**$3,807.45**	**$4,829.15**
TIP Wire Cost per Foot	$4.00 - $6.00	$ 5.00	$1,750.00	$1,750.00	$1,750.00	$1,750.00	$1,750.00	$1,750.00	$2,000.00
TIP Connector	$20.00 - $30.00	$ 25.00	$ 125.00	$ 125.00	$ 125.00	$ 125.00	$ 125.00	$ 125.00	$ 125.00
TIP Wire Install (Labor)	$115.00 - $125.00	$ 120.00	$ 600.00	$ 600.00	$ 600.00	$ 600.00	$ 600.00	$ 600.00	$ 600.00
Total Cost per Shaft for TIP Wire	-	-	**$2,475.00**	**$2,475.00**	**$2,475.00**	**$2,475.00**	**$2,475.00**	**$2,475.00**	**$2,725.00**

The respective total cost for the CSL and TIP consumables and labor is summarized in Table 3. Comparing the installation costs from CSL and TIP testing, there is a potential cost savings of approximately $13,454 U.S. Dollars if only Thermal Integrity Profiling would have been specified for this project. This potential cost savings could reduce the material cost of integrity testing of the drilled shafts by approximately 43% if only TIP testing is specified.

Table 3. Total Cost of Consumables and Labor for Project to Install CSL Tubes and Thermal Wires

	Cost in U.S. Dollars
Total Cost of Consumables and Labor for CSL Tubes	$ 31,029.45
Total Cost of Consumables and Labor for Thermal Wires	$ 17,575.00
Cost Difference	$ 13,454.45
Cost Percentage Difference	43%

ENGINEERING COST COMPARISON

Along with the material costs that are associated with both CSL and TIP testing, there is also the cost of equipment used to collect the data and perform the subsequent analyses. CSL and TIP data are collected in two separate manners. For CSL testing, a trained and qualified person is required to mobilize to the job site and physically collect each of the profiles to be analyzed for each drilled shaft needing testing. For TIP testing a qualified person must mobilize to the site for the first shaft to be tested in order to train onsite personnel, typically consisting of the driller or contractor's crew, on how to install the Thermal Wire® cables. During this initial training the equipment operation, required installation details, and recommended best practices are also covered. Once the data loggers are connected, they transmit the data via cellular connection to a cloud server. After the initial site visit and training, onsite personnel are able to independently install the cables and connect the data loggers so that the engineer can remotely download and analyze the data.

For this project there were a total of seven trips to the job site in order to collect the CSL data and one trip to the site in order to train the driller/contractor on how install the Thermal Cables and attach the data loggers. When including equipment costs, engineering time, travel expenses, and reporting fees for the seven drilled shafts tested the cost per shaft break down is shown in Table 4.

Table 4. Summary of Average Cost for Equipment, Engineering Time, Expenses, and Reports

Test Type	Average Cost per Shaft	Total Cost for 7 Shafts
CSL	$ 1,845.00	$ 12,845.00
TIP	$ 608.50	$ 4,260.00

TIME COST COMPARISON

Installation and data collection are not the only associated costs to a project with NDT testing. Another major factor to be considered when deciding to specify a preferred NDT method is the time impact to the project schedule. As mentioned previously, CSL and TIP both require a certain amount of time before each test can be performed and the results can be analyzed. For this project, CSL testing specifications required the contractor to wait 7 days before the CSL testing could be performed. TIP testing also requires a certain amount of time for the hydration process in the concrete to reach the peak temperature at which time the data is analyzed. Table 5 below summarizes the dates when the drilled shafts were placed as well as the dates when initial CSL testing and TIP testing were performed and analyzed.

Table 5. Summary of Dates for Installation, TIP Testing, and Initial CSL Testing

	Shaft 1	Shaft 2	Shaft 3	Shaft 4	Shaft 5	Shaft 6	Shaft 7
Date Drillled Shaft Installed	5/24/2018	5/22/2018	5/15/2018	5/10/2018	5/8/2018	5/1/2018	4/25/2018
Date of TIP Analysis	5/25/2018	5/23/2018	5/16/2018	5/11/2018	5/9/2018	5/2/2018	4/26/2018
Date of Initial CSL Analysis	5/30/2018	5/30/2018	5/23/2018	5/17/2018	5/17/2018	5/4/2018	5/2/2018

For this project the average time for the concrete mix design to reach the peak temperature was 20.1 hours after concrete placement. The average time at which point initial CSL testing could be performed for this project was 6.9 days or 164.6 hours after concrete placement. Table 6 below summarizes the time difference in hours and days for each of the drilled shafts tested with TIP and the initial CSL with regards to the dates in Table 5.

Table 6. Summary of Time Differences per Drilled Shaft Between TIP and CSL Results

	Time	Shaft 1	Shaft 2	Shaft 3	Shaft 4	Shaft 5	Shaft 6	Shaft 7	Average
Time difference between TIP and CSL Results	hrs	125.5	176	171	146.75	197.5	52	142.75	144.5
	days	5.2	7.3	7.1	6.1	8.2	2.2	5.9	6.0

The average time difference between shaft installation and when the results can be analyzed has a potential time savings for this project of approximately 6.0 days or 144.5 hours per shaft. Using TIP results solely to determine the acceptance or rejection of the drilled shafts for this project would allow the owner and contactor to move forward with the next project activity earlier than if using CSL either in conjunction with TIP or solely. For drilled shafts that do not meet the acceptance criteria this would allow both the owner and the contractor more time to plan for further investigation and or allow remediation efforts to begin sooner.

CSL AND TIP RESULTS COMPARISON

CSL uses ultra-sonic pulses transmitted from a transmitter probe through the concrete and picked up by a receiving probe. By measuring the distance between the CSL access tubes at the top of the drilled shaft and measuring the time at which the signal first arrives at the probe it is possible to calculate an average first arrival time (FAT) through the drilled shaft. By comparing the FAT at different locations to the overall average FAT it is then possible to find potential anomalies in the concrete. TIP testing measures the temperature increase from the hydration process of the cement and water reaction. Data loggers measure the temperature versus depth at 15 minute intervals until peak temperature is reach or until the data loggers are disconnected. The user selected thermal profile between half peak temperature and peak temperature is then used in the analysis along with the reported volume of concrete placed. The volume placed is an integral part of the analysis as it is used to calculate an effective radius. The effective average radius, effective local radii, and cage alignment are assessed in the analysis.

When CSL testing is performed before the concrete has reached a sufficient strength to pass the ultra-sonic pulse the results can be skewed and an inexperienced engineer can determine that the CSL results are unsatisfactory. In an attempt to try to speed up the time from when the concrete was placed and when CSL tests were performed Shaft 6 was tested with CSL after only 2.2 days of concrete curing. The results showed indications of anomalies due to the insufficient concrete strength required for CSL testing to be performed.

CSL testing was then performed again approximately 8 days after concrete placement. At this time, the concrete had sufficient time to gain strength and the CSL results showed no anomalies. Table 7 below presents a summary of CSL and TIP results indicating whether the test reported an anomalous zone or not. The table also shows which drilled shafts were re-tested with CSL testing and the conclusions of the re-test. Seven TIP tests were performed while ten CSL test were performed, including the retesting of Shafts 2, 3, and 6.

Table 7. Summary of Test Results for TIP and CSL

Type of Test	Initial Testing							Re-Test		
	Shaft 1	Shaft 2*	Shaft 3**	Shaft 4	Shaft 5	Shaft 6	Shaft 7	Shaft 2*	Shaft 3	Shaft 6
Anomaly Indicated by CSL Testing	No	Yes	Yes	Yes	No	Yes	No	Yes	No	No
Anomaly Indicated by TIP Testing	No	Yes	Yes	No	No	No	No	-	-	-

*Shaft 2 was required to have further investigation after CSL retest

**Shaft 3 had a reported volume that was 90% of the theoretical volume, later it was determined that the scales at the batch plant were incorrect. No further investigation was required for Shaft 3

The two most concerning results are those of Shafts 2 and Shaft 3. The CSL results for Shaft 2 and Shaft 3 indicated anomalies in the bottom 3.5 feet of the shafts. The TIP results for Shaft 2 indicated a reduction in the effective average radius greater than 6% in the bottom 2 feet. The TIP results for Shaft 3 indicated a reduction in the effective average radius greater than 6% from a depth of 23 feet to a depth of 50 feet below the top of shaft. While Shaft 3 was initially a concern, a CSL retest did not indicate FAT delays. It was determined that the recorded volume placed was incorrect due to an issue with a scale at the batch plant. With the concrete volume placed updated the TIP results did not show evidence of an effective average radius reduction. Thus, Shaft 3 was accepted as is with no further investigation required. The results for Shaft 2 and remediation efforts are further discussed in the following section.

SHAFT 2 - CSL AND TIP RESULTS

CSL results for Shaft 2 indicated FAT delays of 100% in six of the ten profile combinations and FAT delays greater than 30% in the remaining four profiles. The TIP results for Shaft 2 indicated that three of the five cables had a 6% reduction in the effective local radius from 2 to 4 feet above the drilled shaft base, while the remaining two wires had greater than a 6% reduction in effective local radius approximately 1 foot above the drilled shaft base. Part of the TIP analysis involves applying a bottom of shaft adjustment to account for the temperature roll-off to the soil or rock below a shaft. This adjustment is necessary as the base of the shaft represents an additional boundary for heat dissipation. A similar adjustment is applied to the temperature roll-off observed at the top of a shaft. After these adjustments were applied the TIP results indicated an effective average reduction of greater than 6% in the bottom 2 feet of the shaft. Figure 1 shows the reported TIP results in terms of effective radius versus depth. Figure 2 shows a representative sample of the initial CSL results obtained and reported. While the data in Figure 1 appears to be a typical roll-off heat signature the roll-off occurs earlier than what the theoretical model would suggest based adjustment parameters at the bottom of shaft. This early roll-off indicates a zone of lower quality concrete at the base of the shaft.

Figure 1. TIP Results Displaying Radius vs. Depth – Shaft 2

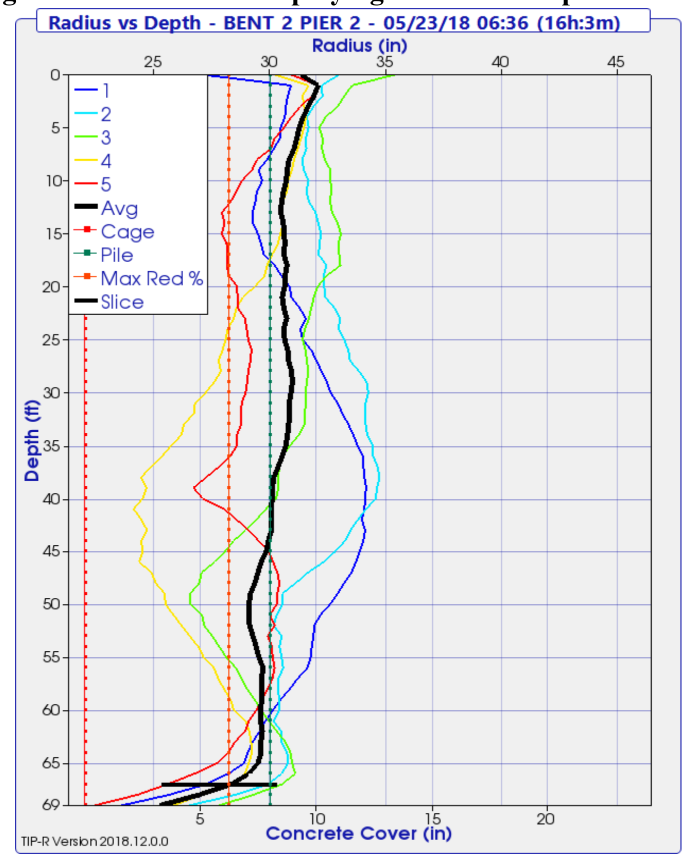
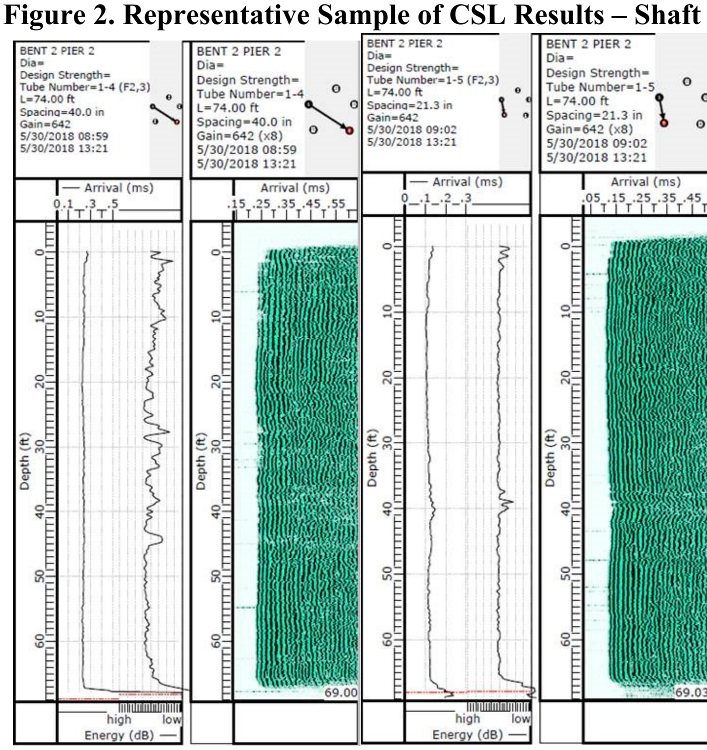


Figure 2. Representative Sample of CSL Results – Shaft 2



After reviewing the CSL and TIP results it was determined that further investigation was required for Shaft 2 in order to confirm the presence of the anomaly detected by both CSL and TIP near the shaft base. Coring was recommended and performed on June 12, 2018. The core results revealed honeycombing (voids and exposed aggregate) in the concrete beginning at a depth of 68 feet below the top of shaft. Lower quality concrete due to contamination was discovered from 68.5 to 70 feet below the top of shaft. Figure 3 presents the cores obtained in the field. Following the coring, the samples were taken back to a lab and tested to assess the compressive strength. Lab results indicated that the concrete in the bottom 2 feet of the drilled shaft had a compressive strength of approximately 1,140 psi. Comparatively, concrete samples tested at 65 feet below the top of shaft recorded unconfined compressive strength of greater than 7,000 psi. After the core results were presented to the Engineer, it was determined that hydro-blasting and pressure grouting was required to remediate the anomalous zone. Following the pressure grouting, additional CSL testing was performed to verify that the grout was able to flow in the bottom of the drilled shaft and remediate the issue. Table 8 compares the initial CSL results with the retest CSL results that were performed after hydro-blasting and pressure grouting was completed.

Figure 3. Pictures of the Cores Recovered from the Bottom of Drilled Shaft 2.

Core Samples NQ-13 to NQ-15: From left to right top core starting at a depth of 59.0 feet and bottom of core ending at 70.0 feet.

Table 8. Summary of Initial CSL and Post Grouting CSL Results

Profile	Max FAT Delay (%) 5/30/2018	Max FAT Delay (%) 6/15/2018
1-2	100	41
1-3	100	25
1-4	100	32
1-5	92	51
2-3	52	37
2-4	34	22
2-5	56	28
3-4	100	53
3-5	100	26
4-5	100	32

CONCLUSION

In summary for the project presented for this paper, seven drilled shafts were tested using both CSL and TIP. The results from the two different test methods were used in conjunction to determine the acceptance of the shaft or if further methods of evaluation were required. After the project had been completed a comparison study was performed for the financial costs, time impacts, and results associated with each of the test methods.

Overall, the findings from the data provided from this project show that Thermal Integrity Profiling can be a cost-effective alternative to traditional Cross Hole Sonic Logging. The material cost for CSL testing was calculated by including the cost of the access tubes, tube caps, labor to install CSL tubes, and the post grouting of CSL tubes. The material cost for TIP testing was calculated by including the cost of Thermal Wire® cables, TIP connection per wire, and the labor to install the wires. The material costs for CSL and TIP testing were calculated to be $31,029.45 and $17,575.00, respectively. This equates to a cost difference of $13,454.45 USD or a 43% cost difference. Additionally the cost comparison of collecting and interpreting the data revealed that for this project the cost of CSL and TIP testing was $12,845 and $4,260, respectively. This equates to a cost difference of $8,585 USD or a 67% cost difference. Therefore the total costs which includes the material cost, engineering cost, data collection, data analyses, and reporting fees for CSL and TIP testing are $43,874.45 and $21,835, respectively.

The data provided for this paper also shows that there is a potential for significant time savings or potential for an accelerated schedule. Both CSL and TIP testing requires a waiting period before the data can be obtained. In general CSL has a 7 day waiting period before the test can be performed while TIP data loggers collect data continuously from the end of concrete placement until the peak temperature is achieved. Peak temperature generally occurs between 10 to 48 hours after concrete placement. For this project TIP results were obtained on average approximately 24 hours after concrete placement, while CSL results could not be obtained until a minimum of 7 days after concrete placement. Therefore is TIP testing was the only specified method of testing for this project the average time that could have been saved between results being obtained was 6 days.

Determining a potential flaw or anomaly in the concrete is the main objective of both CSL and TIP. Traditionally only one of the two test methods is generally specified for a given project. While this is industry standard, the limitations of either test can return false positives and therefore require expensive additional investigations to confirm the NDT results. For this project, the initial testing CSL results indicated that four of the seven drilled shafts could have potential anomalies. From the initial testing results from TIP testing two of the seven drilled shafts were reported to have potential anomalies. If only CSL testing was performed for this project, Shaft 6 could have been classified to have an anomalous zone after the first CSL test was performed. With the addition of TIP testing on this project, it was determined that an additional CSL test was required which confirmed the TIP results were correct. Without TIP testing, coring could have been required on Shaft 6. Shaft 2 was discussed in detail in this paper and both CSL and TIP results both indicated that there was a potential anomaly in the bottom two to three feet of the drilled shaft. After further investigation was completed, it was confirmed that both CSL and TIP detected an area of concrete that had lower compressive strength than desired. If only TIP testing was required for this project it would have been difficult to assess the success in post grouting. Without CSL being specified coring most likely would have been required to determine if the post grouting was successful or not. CSL offered the advantage of being able to run another CSL test after post grouting and verify that grout was able to flow between the grout access cores. As long as the Thermal Wire® cables have not been cut at the top or damaged due to the hydro blasting it is possible that the data loggers could be connected to the cable and temperature readings could be measured during the curing of the grout.

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