Concrete Strength Variation and Curing Effect on the Crosshole Sonic Logging (CSL) Results of Cast-in-place (CIP) Concrete Piles

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ABSTRACT
Crosshole Sonic Logging (CSL) test is mandatory for concrete placed under water in Alberta Transportation bridge pile construction projects. This study provided a case study of the concrete strength variation and its effect on the CSL rating performed on a recent Calgary Ring Road bridge project. The initial CSL tests revealed that 11 out of 46 tested piles exhibited possible anomalies. Further Tomography Analysis on the 11 piles indicated that two piles had very low effective area, two piles had slightly lower effective area, while two other piles showed “No Signal”. Further CSL retests proofed that prolonged concrete curing could improve CSL ratings, but not effective on the pile with “No Signal”. Direct concrete coring results showed no visual physical defects in concrete, but the strength variation would lead to an unacceptable CSL rating. Overall, the CSL testing is considered to be a very sensitive testing method and is capable of detecting any variation in concrete strength along the pile shaft.

RÉSUMÉ
Le test Crosshole Sonic Logging (CSL) est obligatoire pour le béton placé sous l'eau dans les projets de construction de pieux de pont de l'Alberta Transportation. Cette étude a fourni une étude de cas de la variation de la résistance du béton et de son effet sur la cote CSL réalisée sur un récent projet de pont du périphérique de Calgary. Les tests initiaux de CSL ont révélé que 11 des 46 pieux testés présentaient des anomalies possibles. Une analyse tomographique plus poussée sur les 11 pieux a indiqué que deux pieux avaient une surface effective très faible, deux pieux avaient une surface effective légèrement inférieure, tandis que deux autres pieux affichaient "Aucun signal". D'autres tests CSL ont prouvé qu'un durcissement prolongé du béton pouvait améliorer les cotes CSL, mais pas efficace sur le pieu avec "Aucun signal". Les résultats directs du carottage du béton n'ont montré aucun défaut physique visuel dans le béton, mais la variation de résistance conduirait à une cote CSL inacceptable. Dans l'ensemble, l'essai CSL est considéré comme une méthode d'essai très sensible et est capable de détecter toute variation de la résistance du béton le long du fût du pieu.

1 INTRODUCTION

Cast-in-place (CIP) concrete piles are one of the most common foundation types for bridge and building in Alberta (Sau et al., 2018). Compared to other deep foundation piles, CIP concrete piles have potential advantages of larger diameter (>1.2 m), higher load-carrying capacity, less pile settlements, and can provide high resistance to corrosive underwater environment (Garder et al., 2012). Due to natural of underwater construction, seepage from the groundwater flow or aquifer is usually quite severe during concrete pile installation. The presence of water could raise concerns about CIP pile integrity for long-term performance (O'Neill and Sarhan, 2004). Therefore, a post-installation quality control measurement of concrete integrity is critical for the pile foundation.

Crosshole Sonic Logging (CSL) is one of the most common integrity testing methods for concrete piles (Mullins and Winters, 2011). CSL has a proven record for identifying defective concrete in pile shaft. CSL determines the quality and consistency of the concrete of foundation piles. The CSL pile integrity test is performed in accordance with the ASTM D6760-16 (ASTM, 2017). Generally, the CSL test measures the propagation time and relative energy of an ultrasonic pulse between parallel access tubes (crosshole), which are installed along the rebar cage of the large, bored concrete piles.

However, subsequent pile investigation and remediation method is not very well defined after anomaly detected by CSL testing (Li et al., 2005). From the recent CSL testing program of bridge piles in Calgary, Alberta, it was noticed that the concrete strength variation along the shaft and concrete curing duration would affect CSL testing results. In other words, the CSL records are sensitive to the inherent properties of concrete.

The objectives of this case study are as follows:

- Review the existing soil information including geotechnical investigation and soil laboratory testing results.

- Prepare summary of field observations including pile installation logs, CSL measurement and pile coring logs as provided in Sections 3.1 and 3.2.

- Quantitative review of concrete curing effect on the CSL ratings.

- Visual verification of concrete quality through coring.

- Recommendations for further pile integrity investigation and based on proposed CSL rating category.

2 PROJECT DESCRIPTION

The studied Alberta Transportation bridge is located at northwest Calgary over Bow River near Trans Canada Highway 1. The bridge foundation consists of 4 piers and 2 abutments. Each pier is found on 18 to 28 CIP concrete piles with a diameter of 1.22 m with design unfactored ultimate pile loads ranging from 9,770 to 11,100 kN per pile. The as-built pile embedment depths ranged from 12 to 17 m. In this study, only Pier 1 and Pier 2 piles were studied due to the availability of CSL testing results.

2.1 Site Location and Local Geology

The Piers 1 and 2 are located at the south bank of Bow River in northwest Calgary. The soil profile at Pier # 1 was described as, in descending order: fill, clay till with sand lenses overlying interbedded claystone, siltstone and sandstone bedrocks. The soil profile at Pier # 2 was described as, in descending order: fill, gravel, silty sand overlying interbedded claystone, siltstone and sandstone bedrocks. The CIP concrete piles were designed with only shaft friction socketed into the local sedimentary bedrock formations based on the following shaft friction parameters provided in site geotechnical investigation summary report.

Table 1. Soil Parameters for Pile Design

	Factored Pile Shaft Friction (kPa)	
Rock Type	Pier 1	Pier 2
Claystone	150	175
Siltstone	375	435
Sandstone	675	785

2.2 CIP Pile Installation

The most significant challenge in bridge foundation installation is sloughing and groundwater seepage inflow into the pile holes. Temporary segmental casing was used throughout the auger boring process to prevent shaft sloughing and seepage. Due to very high hydrostatic pressure at the bottom of the drilled hole, groundwater was constantly filing up the drilled hole from the pile bottom. To handle underground concrete pouring, tremie method was implemented for all pier pile installations.

Due to the temporary casing was removed after concrete placement, and possible contact and intrusion of sloughing loose material or groundwater seepage, CSL testing was performed as per AT bridge specifications.

2.3 CSL Testing and Analysis

2.3.1 CSL Testing and Rating

A Cross-Hole Analyzer™ Model CHAMP was used to acquire and process the data. CSL data was collected from each paired CSL tubes. Basically, the transmitter and receiver probes were lowered to the bottom of the access tubes, and slowly pull the probes up. The signal transferred between the two probes will be recorded in a 5 cm interval during the pull-up process. Lengths and spacing of the access tubes were measured and recorded for CSL results interpretation.

The data was analyzed using CHAMP's CHA-W software to provide signal first arrival time (FAT). Pile shaft integrity can be evaluated based on the consistency of signal FAT and/or velocity reduction between the CSL tubes. Interpretation of the CSL test results was performed according to the Alberta Transportation Standard Specifications for Bridge Construction – Edition 16, 2017 Table 3-1: CSL Condition Ratings as shown in Table 2 [1].

Table 2. CSL Test Result Ratings

Rating	Velocity Reduction / FAT Delay
Good (G)	≤10%
Questionable (Q)	>10% & <20%
Poor/Defect (P/D)	≥20%
No Signal (NS)	No Signal Received

The project specification stated that any rating other than Good (G) would not be considered acceptable and subject to review of the CSL report by the project engineer. The contractor was required to submit a remedial action plan for any pile that was not accepted by the engineer.

2.3.2 Tomography Analysis for Effective Pile Cross Section Area

For piles with poor CSL ratings, additional tomography analysis was performed by using PDI_TOMO software to better assess and quantify anomalies noted in the concrete material of the shaft from the CSL data. This software combines arrival time data from the scans of all pairs of tubes, analyzes the data, and displays the analysis results in various 3-D views.

The Tomography analysis calculates an effective area based on defined effective wave speed which is about 90% of the average wave speed. The effective area is the ratio of the cross-sectional area at a selected depth with wave speeds greater than the effective wave speed, compared to the total cross-sectional area.

3 CSL TEST RESULTS

3.1 FAT Delay Ratings

The first step of determining the pile rating was direct comparison based on FAT delay results of CSL measurements. 11 out of 46 tested piles indicated some levels of FAT delay of more than 10% throughout the pile shaft.

3.2 Anomaly and Tomography Analysis

For those 7 piles which were rated other than “G”, tomography analysis was further performed to evaluate the effective cross-section areas of the concrete caisson. A summary of tomography analysis results of those piles is provided in Table 3. Based on the tomography results, only 5 out of 11 piles are deemed to have a minimum effective area of 90% which is acceptable. Piles P1-02 and P1-15 are identified with a layer of shaft that has no signal transferred between the access tubes. Piles P1-10 and P2-06 display relatively low effective area (29% and 37%) from the tomography analysis. This indicates that piles may contain possible defect at those depths. The effective area of Piles P1-12 and P2-09 are 72% and 84%, which are slightly lower than the minimum required one which indicated possible flaws. These remaining 6 piles are subjected to further investigation through CSL retests or direct concrete coring.

Table 3. Summary of Tomography Analysis

Pile ID	Anomaly Summary	
	Depth (m)	Effective Area
P1-02	7.4 to 7.8	0%
P1-10	7.8 to 8.05	29%
P1-12	7.6 to 8.1	72%
P1-15	3.4 to 4.3	0%
P1-16	12.7 to 12.8	98%
P1-17	12.8 to 12.9	97%
P2-15	15.88 to 16.03	90%
P2-20	16 to 16.04	90%
P2-06	0-1.5	37%
P2-08	15.51 to 15.81	97%
P2-09	15.50 to 15.75	84%

Piles P1-16, P1-17, P2-08, P2-09, P2-15, P2-20 were acceptable based on the engineering assessment. For Pile P2-06, due to the anomaly was identified near the pile top surface, a visual inspection was performed to verify the pile top concrete condition which was intact. The FAT delay of Pile P26 was likely contributed to access tube spacing variation due to tube bending near the pile head.

4 FURTHER INVESTIGATION OF PILE INTEGRITY

4.1 CSL Retests

Piles P1-02, P1-10 and P1-12 were retested to verify if further concrete curing would improve the CSL ratings. Table 4 shows a summary of retesting results of those three piles.

It is noted that Piles P1-10 and P1-12 have reached the satisfactory rating during the CSL retests at 33 and 35 days after concrete placement. However, Pile P1-02 indicates no improvement from “No Signal (NS)” during the retest. Piles P1-10 and P1-12 exhibit signal transferred during the original test, which have been also improved with additional concrete curing.

Table 4. Summary of CSL Retest Results

P1-02		P1-10		P1-12	
Curing Days	Effective Area	Curing Days	Effective Area	Curing Days	Effective Area
7	0	6	29	7	72
17*	0	15*	45	35*	97
-	-	33*	100	-	-

*Retests.

Variations of effective cross-section area versus concrete curing time are illustrated in Figure 1.

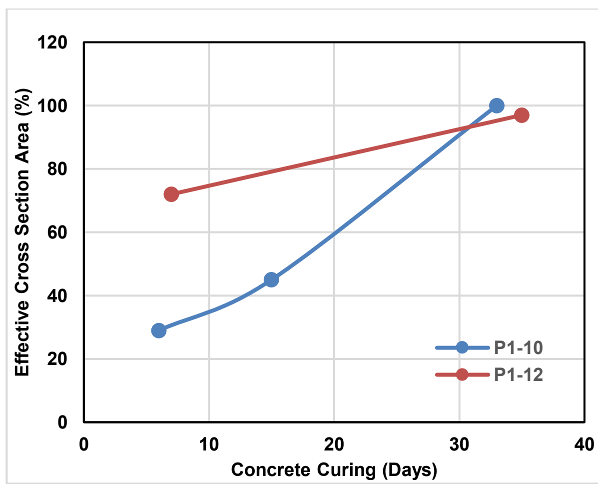

Figure 1. Effective Cross-Section Area vs Concrete Curing Time

4.2 Concrete Coring and Inspection

After CSL retesting, Piles P1-02 and P1-15 still indicate potential issues of concrete integrity or possible debonding of CSL access tubes. However, it is not very like that all four access tubes all deboned at the same depths. Therefore, a coring plan was proposed to visually inspect the concrete condition for Piles P1-02 and P1-15. Based on tomography analysis results, the proposed coring locations are depicted in Figures 2 and 3.

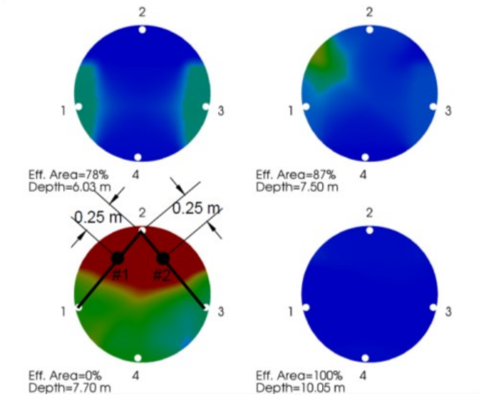

Figure 2. Proposed Coring Hole Plan for P1-02

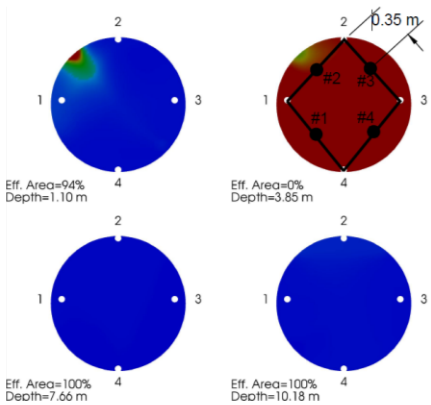

Figure 3. Proposed Coring Hole Plan for P1-15

A sample photograph of cored concrete from Pile P1-15 is shown in Figure 4.

Figure 4. Concrete Core from pile P1-15

From on-site core inspection, no physical concrete integrity problems such as voids or other abnormalities are observed at the questionable depth of each pile. However, the compressive strength test of the concrete cores has indicated a relatively large variation in compressive strength, as summarized in the following table.

Table 5. Summary of Concrete Core Test Results

P1-02			P1-15		
Core Hole ID	Depth (m)	Comp. Strength (MPa)	Core Hole ID	Depth (m)	Comp. Strength (MPa)
1	7.43 – 7.83	39.1	1	3.37 – 4.27	50.2
2	7.43 – 7.83	51.4	2	3.37 – 4.27	35.4
3*	7.43 – 7.83	44.2	3	3.37 – 4.27	46.8

**Extra hole #3 was cored for P1-02*

The axial compressive strengths of concrete cores collected at anomaly zones are verified to be varied from 39.1 to 51.4 MPa of Pile P1-02, and 35.4 to 50.2 MPa of Pile P1-15.

5 DISCUSSION AND CONCLUSIONS

This study examines the different types of CSL anomaly indicated from a bridge foundation project. The following recommendations are proposed for future CSL anomaly assessment based on levels of FAT delay:

- The first type of anomaly indicated the FAT delay with low signal strength. Retesting of this type of pile could possibly yield improvement in CSL rating due to potential concrete curing and reduction in concrete strength variation.

- The second type of CSL anomaly indicated no signal transferred between CSL access tubes. The retesting results of second type piles did not indicate any improvement in effective cross section area, therefore, visual inspections were followed.

Due to CSL methodology utilizes ultra-sonic signal, which is not a direct measurement of concrete strength, visual inspections are required to assess the pile integrity / concrete quality. For this studied site, fortunately, no physical defects were observed on the cored samples even no CSL signal was transferred at certain pile depths. It was noted that the concrete compressive strengths of cored samples varied about 24% and 30% for P1-02 and P1-15, respectively.

Considering the wave speed of concrete is related to the compressive strength which means concrete with higher strength should consist of higher wave speed. The CSL testing method assumes uniform pile concrete and consistent wave speed throughout the pile shaft. Based on this assumption, the pile concrete quality can be assessed. Therefore, it is suspected that large concrete strength variation contributed to CSL anomalies.

From the findings of this CSL program, the following advantage were noted:

- CSL is generally a cost-effective QC verification for large diameter caisson installed below groundwater table considering only the access tubes are sacrificial materials. Equipment is reusable and required field testing times are manageable (less than 2 hours per test).

- CSL data is recorded in 5 cm interval which is considered to be quite sensitive with high resolution for concrete variation along the shaft. If CIP concrete pile obtained a satisfactory rating from CSL testing, the pile concrete quality within an area bound by the access tubes can be reliably considered to be sound.

The following limitations of CSL were also noted:

- Only concrete between the access tubes were tested from CSL. Due to access tubes are tied to the rebar, concrete cover outside of rebar area can not be tested by CSL.

- The high sensitivity of CSL measurements could yield false negative results due to minor concrete strength variation.

6 REFERENCES

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