Thermal Integrity Profiling of ACIP Piles

Matthew L. Becker[1], A.M. ASCE, Travis L. Coleman, P.E.[2], and Daniel S. Belardo[3]

[1]Engineer, GRL Engineers, 30725 Aurora Road, Cleveland, Ohio. 44139. E-mail: mbecker@grlengineers.com
[2]Senior Engineer, GRL Engineers, 1540 E Dundee Road, Suite 102, Palatine, IL. 60074. E-mail: tcoleman@grlengineers.com
[3]Project Manager, GRL Engineers, 30725 Aurora Road, Cleveland, Ohio. 44139. E-mail: dbelardo@grlengineers.com

ABSTRACT: Augered Cast-in-Place (ACIP) piles are often utilized as a deep foundation solution for certain soil conditions. Rapid production allows for shorter construction schedules while depths and diameters continually increase in scale. Quality assurance of ACIP piles generally relies upon installation monitoring as well as post construction integrity testing. A relatively new testing technique is Thermal Integrity Profiling (TIP). For relatively small diameter ACIP piles, a cable comprised of temperature sensors is attached along the center rebar, and placed in the grout of the ACIP column, such that temperature measurements can be recorded during the cement hydration process. These measurements are then post processed, along with installation records, to assess overall ACIP pile integrity. A project site in Rockport, Indiana utilized over 400 ACIP piles which had integrity analysis performed via TIP. In addition, pulse echo testing and dynamic load testing was performed on a small number of test piles. This paper presents a case study on techniques of TIP instrument installation and data analysis as well as a discussion of recommendations for future use.

INTRODUCTION

Augered Cast-in-Place (ACIP) piles are often utilized as an alternative deep foundation type. They generally provide for automated monitoring upon installation and typically, rapid construction allows for shorter construction schedules (Brown et al, 2007). Quality assurance of ACIP piles relies upon installation monitoring as well as post construction integrity testing, the latter of which is subject to the testing engineer's interpretation.

Integrity test methods most commonly used are the pulse echo test and variations of sonic hole testing. However, a relatively new testing technique called Thermal Integrity Profiling (TIP) is becoming a more utilized alternative. For this test, temperature measurements are recorded during the hydration of cement and are post processed to assess overall ACIP pile integrity. Bulges, necks, cage alignment issues, poor quality concrete etc. may be interpreted from the post processing results to provide a better understanding of any integrity issues with the ACIP pile. Thermal Integrity Profiling is unlike other integrity methods available as the test is performed during, as opposed to after, the curing process.

Thermal Integrity Profiling was used at a project site in Rockport, Indiana where over 400 ACIP piles were installed to depths of 20.7-m to 22.3-m (68-ft to 73-ft) into primarily sandy soils. A cable consisting of temperature sensors, spaced at every foot along its length, was attached to the center rebar. After cage insertion into the wet grout column, the cable was connected to a data logger known as a Thermal Acquisition Port (TAP) box. Temperature measurements were then recorded for approximately 24 hours, at which time project personnel disconnected the data logger to download and email data files the TIP Consultant.

Instances of damaged temperature sensors or an entire temperature cable were within expected limits based upon the installation method, while the percentage of piles analyzed via TIP met the project owner requirements. A comparison between TIP, pulse echo testing and dynamic load testing for a limited amount of piles was performed. Overall, thermal integrity profiling for this project provided acceptable, reliable results and improved confidence with this test method.

CURRENT INTEGRITY TESTING METHODS

Integrity testing of ACIP piles is performed primarily by low strain impact testing, cross hole sonic logging or single hole sonic logging. Thermal Integrity Profiling is becoming a more viable option to replace these testing methods. These tests all require training to perform testing or installation, while the results require review by an experienced engineer to determine suitable integrity.

Low Strain Impact Integrity Testing

A common deep foundation integrity test method is low strain impact integrity testing or the pulse echo test, which is performed in accordance with ASTM D5882. This may be performed with the Pile Integrity Tester (PIT). At minimum, an accelerometer attached to the constructed pile top measures a small hammer induced velocity wave (e.g., Brown et al, 2007). The wave travels through the pile, reflecting off of abnormalities such as necks or material changes including voids and the pile toe. These signals are then transmitted to a processing unit, where a basic field assessment may be made. Figure 1 shows the PIT equipment and testing configuration while Figure 2 displays data recorded during the test. Please note, the data presented here was post processed following the field test.

Pulse echo testing is performed no earlier than 7-days after the foundation element is constructed, with minor prep work: grinding a smooth, flat surface to attach the accelerometer. This test method is relatively economical, and depending on site conditions, many foundations elements may be tested in a single day. However, the induced stress wave decreases in amplitude as it travels down the pile, reducing the test's ability to locate defects or the pile toe, with greater depth. Generally this is caused by soil damping or pile irregularities, thus limiting pulse echo testing to length/diameter (L/D) ratios of about 30 (Morgano, 2013). Some cases allow for larger L/D ratios up to about 45 with useable results (i.e favorable soil conditions), yet instances of missed defects or failure to view the pile toe reflection entirely, do occur (Fig. 2a)

FIG 1. Pile Integrity Tester with Instruments

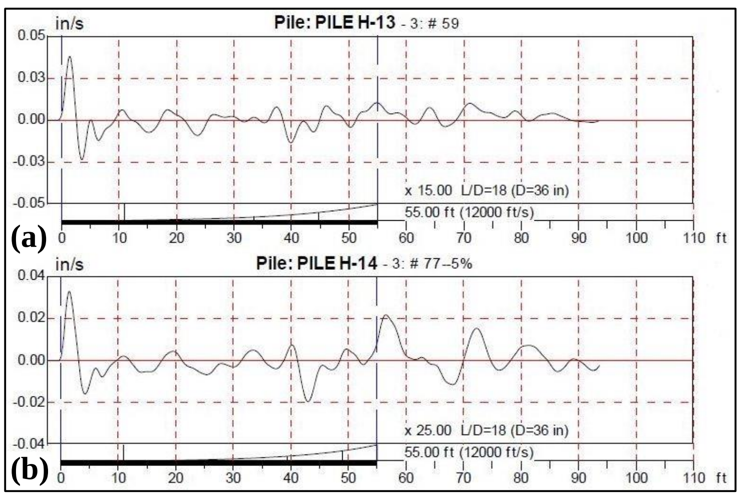

FIG. 2 PIT Data: (a) No Toe Reflection, and (b) Clear Toe.

Cross Hole and Single Hole Sonic Logging

Cross hole Sonic Logging (CSL) is performed primarily on drilled shafts, but may also be performed on other cast in place deep foundation elements and is performed in accordance with ASTM D6760. Steel or PVC access tubes are tied to the rebar cage during construction. Sonar probe recordings are then taken between these tubes after the concrete is poured. Figure 3 below shows CSL tubes tied to the deep foundation cage, while a four tube shaft test pattern is displayed in Fig. 4.

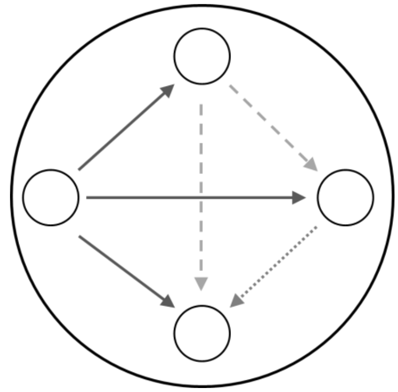

FIG. 3. CSL Tubes in Drilled Shaft **FIG. 4. CSL Test Path Permutations**

Changes in the signal arrival time vs depth are recorded for multiple tube paths, and allow for an engineer's determination of anomalies, such as areas of low quality concrete or possible voids. The probe-in-tube transmission process for CSL is presented in Fig. 5.

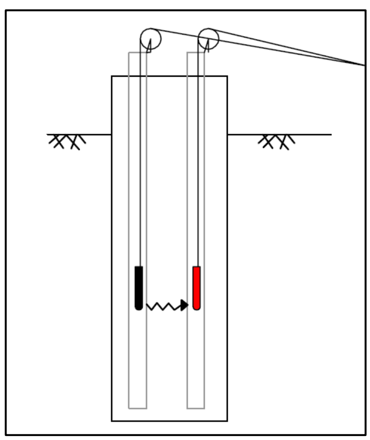

FIG. 5. CSL Probe to Probe Transmission

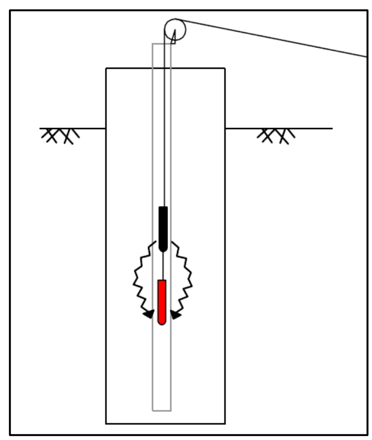

FIG. 6. SSL Probe to Probe Transmission

For foundations without rebar cages, such as some ACIP piles, a single PVC tube is attached to the center rebar, or pushed through wet concrete if no rebar is utilized. This configuration requires Single Hole Sonic Logging (SSL), whereby both probes are in the same tube. Sonar signals are transmitted and received from probes along a vertical axis, which is shown in Fig. 6

As previously mentioned, the sonar signal for both CSL and SSL is measured from probe to probe, thus eliminating effects of the surrounding soil. Sonic logging records may locate anomalies located within the path of the probes' transmission signal. Anomalies outside this path (i.e., outside the rebar cage or not in the direct transmission path) are often unable to be assessed, including many bulges or necks (Morgano, 2013). In addition, locating shaft issues may become more difficult if too few access tubes are installed.

Another concern may be debonding of the access tubes and concrete interface. This may occur with PVC tubes and appropriate steps must be taken to acquire useable data. Bleed water may also contribute to a delayed signal and appear as either debonding or an anomaly. For the SSL case specifically, signal scatter may come into question for interpretation of certain indicated defects, as the signal must transmit in an arcing manner.

Thermal Integrity Profiling

A relatively new integrity test method is Thermal Integrity Profiling (TIP). This test method evaluates heat generation as cement hydrates, where differences in temperature measurements are utilized to assess shaft integrity. Testing may be performed with a downhole temperature probe, or embedded temperature sensors that are attached to the foundation's rebar (e.g., Likins and Mullins, 2011; Mullins, 2010; Sellountou et al, 2013). Although TIP is primarily used for drilled shafts, this test may also be used for other applications (e.g. ACIP piles, jet-grouted columns, soil nails). Generally, peak temperature records are analyzed with respect to the installed volume of concrete to determine an effective radius, as well as the location of anomalies such as bulges, necks, voids or even reductions in quality. The effective radius is expected to be the design shaft radius and is defined as that radius of intact uncompromised concrete that would produce the measured temperature.

FIG. 7. Thermal Probe Test

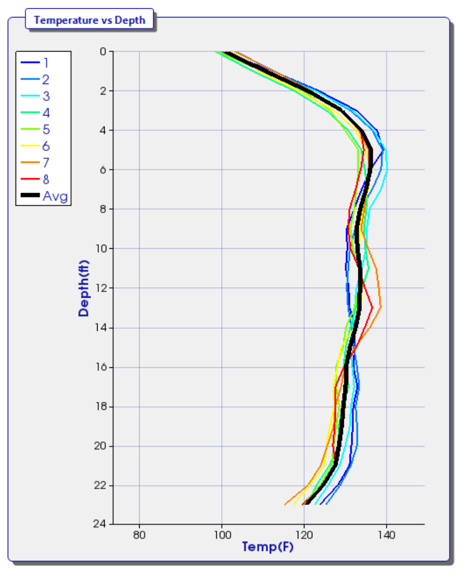

FIG. 8. Temperature Recordings

The probe method of TIP involves casting access tubes in the foundation element during construction. A dewatered steel access tube is recommended for thermal testing. As shown in Fig. 7, a temperature probe is inserted into the access tube approximately 12 to 48-hours after placement (during peak temperature), and travels the shaft length recording temperature with depth. This test is time sensitive due to the nature of curing cement; as the hydration process slows, the shaft temperature and variations in temperature decrease and measurements may become more difficult to interpret. Results are typically plotted as temperature vs depth and later interpreted for acceptable integrity (Fig 8). Time windows for recording the peak temperature, based on design shaft radius, have been recommended in previous research (Mullins and Piscsalko, 2012).

Thermal profiles may also be generated by the wire method. For this, cables consisting of incrementally spaced digital temperature sensors are attached to the longitudinal bars of the reinforcing cage, usually by zip ties (Fig. 9). Typically, cables are equally spaced around the cage similar to access tubes. After the shaft is poured, each cable is connected to a Thermal Acquisition Port (TAP) as shown in Fig 10. This collection unit samples temperature measurements at preset intervals (i.e. 15 minutes), or according to the engineer's recommendation. Collection continues throughout the hydration process, and therefore the peak temperature is naturally acquired, thus eliminating possible collection timing issues as compared to the probe. Data is then post processed similarly to the probe method to ensure shaft quality and locate anomalies, if any.

FIG. 9. Thermal Wire® cable on Rebar

FIG. 10. TAP Data Collection Unit

Constructed test shafts have compared well for CSL and PIT to TIP (e.g., Mullins and Winters, 2011; Piscsalko, 2013; Sellountou et al, 2013). Bulges, necks, and poor quality concrete have been correctly identified and located. Additionally, cage alignment issues have been discovered by using TIP, as well as any anomalies outside the rebar cage, which may be missed by CSL.

Based on the scale of drilled shafts, TIP data collection is usually completed within 12 to 48-hours of the foundation element construction. Therefore, QA/QC test results may be provided in a timelier manner as compared to other testing techniques. The probe method of TIP provides for a quick measurement of temperature versus depth, however access tubes are required. If using embedded temperature sensors, test timing issues are virtually eliminated, as bulk sampling typically captures the peak temperature. Contractors or inspectors may be tasked with installing the cable and retrieving data, thus reducing engineer on-site time. The embedded temperature cables are sacrificial, as they are cast into the foundation element.

CASE STUDY: CONTINUOUS FLIGHT AUGERED PILES IN SOUTHERN INDIANA

An expansion was planned for an existing power plant in Rockport, IN. Several new structures were to be built, including two 36.6-m (120-ft) tall storage silos, referred to as Unit 1 and Unit 2. Driven piles, micropiles and ACIP piles were shortlisted as the foundation options. Eventually, ACIP piles were selected, with each unit requiring 222 ACIP piles. Due to the project's ACIP pile design integrity testing that provided reliable, accurate and relatively economical results proved to be a challenge. Pulse echo testing would be outside of the normal range of its L/D ratio limit, and SSL would require a large amount of onsite engineering time and provide limited results. Moreover, TIP was offered as a testing alternative and accepted by the project owner and the project engineer to ensure adequate foundation integrity.

Soil Profile

A subsurface investigation program included borings and cone penetration testing. At Unit 1 and Unit 2, sandy clay and silty clay material overlie sands with trace gravel and silt down to borehole termination. Groundwater stabilized at about 8.5-m (28-ft) below the surface. Figure 11 provides a generalized soil profile for the two locations. Cone penetration tests provided affirmation of the boring results.

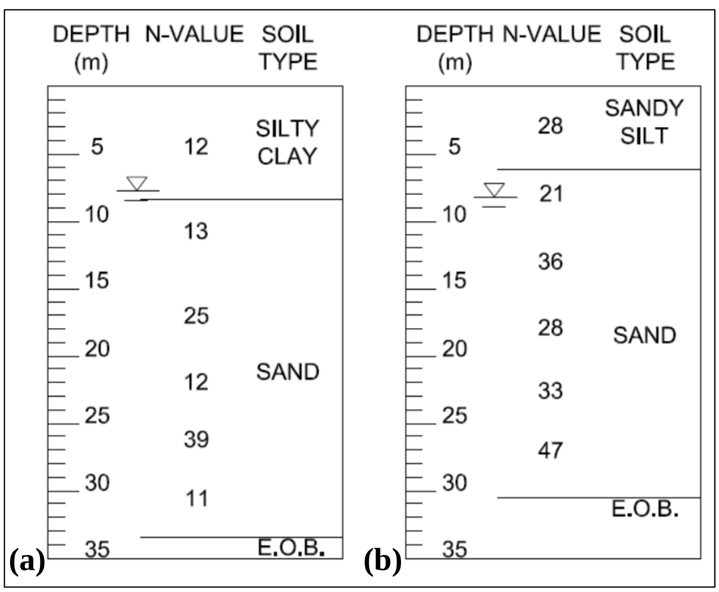

FIG. 11 Soil Profile for (a) Unit 1 and (b) Unit 2

Deep Foundation System

The new 36.6-m (120-ft) tall structures had significant lateral loads, overturning moments, and high bearing pressures which required a deep foundation system. Economy and general performance in sandy and gravelly soil led to the selection of ACIP piles over driven piles and micropiles. The Unit 1 piles were installed to a depth of 22.3-m (73-ft) and the Unit 2 piles were installed to a depth of 20.7-m (68-ft), while piles at both units had a nominal diameter of 45.7-cm (18-in). Half the piles in each unit were instrumented with Thermal Wire® cables, and of these approximately 40 percent were randomly selected for integrity analysis as means of quality control.

Testing Program

For thermal integrity profiling, the quality control process began before a pile was constructed. The ACIP pile design on this project called for a single, center rebar to extend the pile length with a seismic hook laden reinforcing cage along the upper portion of the pile. Multiple temperature cables were not a viable option since the reinforcing cage terminated halfway down the pile. Moreover, a single temperature cable was secured to the center rebar of the each ACIP pile selected for testing. Zip-tie secured cables are shown in Fig. 12 while a close up view of the digital temperature sensor is presented in Fig. 13. Following an initial training session by the TIP Consultant, cable installation and data collection was left to the site inspectors.

FIG. 12. Prepped Center Rebar

FIG. 13. Single Temperature Sensor

During ACIP pile construction, an instrumented center rebar was inserted into the column of grout immediately after the auger was extracted. The reinforcing cage was then placed around the center rebar, and once set, a TAP data collection unit was connected to the respective Thermal Wire® cable. Once connected, temperature measurements were collected every 15-minutes. This interval was selected based on pile size and project requirements. Data collection commenced shortly after each respective pile was constructed, and the overall project time to peak temperature was approximately 13-hours. However, data collection normally continued for approximately 24-hours. Figure 14 shows the time to peak temperature distribution with 30-minute bins. For a few piles, data collection may have begun a significant time after placement, resulting in an early measured time to peak temperature. After the peak temperature was reached, data was downloaded from the data collection unit and sent to the TIP Consultant for processing. Data was analyzed with the TIP Reporter, which converts raw field data into graphical outputs.

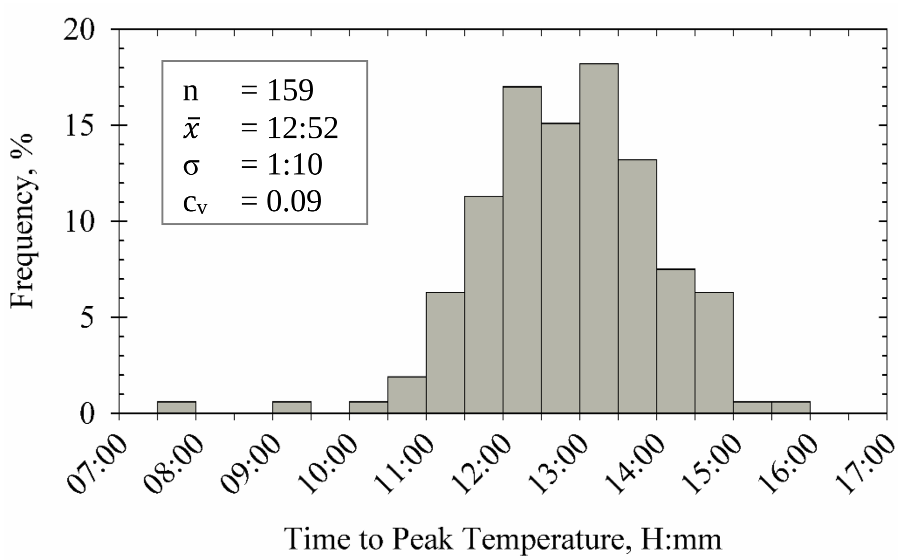

FIG 14: Time to Peak Temperature Distribution

Data Analysis

Of the 444 total installed ACIP piles, 221 were instrumented with temperature cables. Furthermore, 88 underwent full analysis (i.e. 20% of the total) per the project requirements, while 10 of these analyzed piles were also subjected to low strain integrity testing and dynamic load testing. No major defects were discovered in any of the evaluated ACIP piles or during dynamic load testing.

The measured temperature vs depth is presented in Fig 15a for Pile A-1. Measured temperature remains relatively constant along the pile length, varying from 43˚C to 49˚C (109˚F to 121˚F). Slight temperature roll offs at the top and bottom of the pile are normal, and represent boundary conditions of larger areas for heat transfer to the ambient air and soil at the pile toe. Based on thermal profiling, Pile A-1 has an effective radius of 28-cm (11-in), which would exceed the design radius of 23-cm (9-in) (Fig 15b). Since the cable was placed along the center rebar for this ACIP pile, the radius and concrete cover are equal.

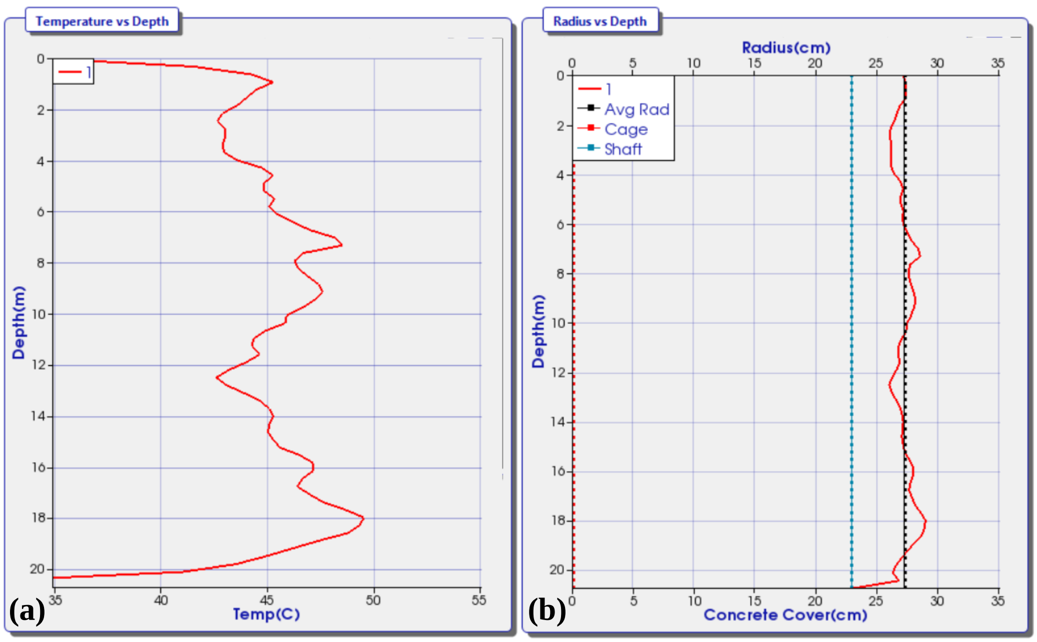

FIG 15: (a) Temperature vs. Depth and (b) Radius vs. Depth: Pile A-1

Based on the recorded temperature signature, a relatively uniform shape is maintained along the length of this pile, and uniform quality grout was placed through the entire depth of 20.7-m (68-ft). A rendering of the three dimensional ACIP pile was then created with the cage, or center rebar, in Fig. 16a and the pile exterior only in Fig. 16b.

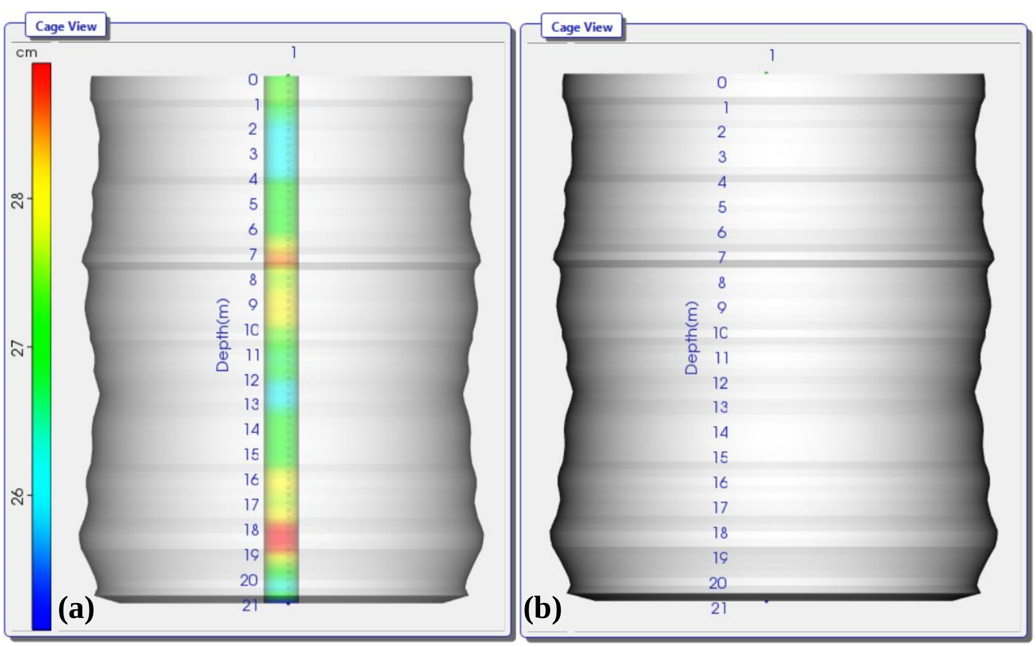

FIG 16: 3-D Interpretation: Pile A-1

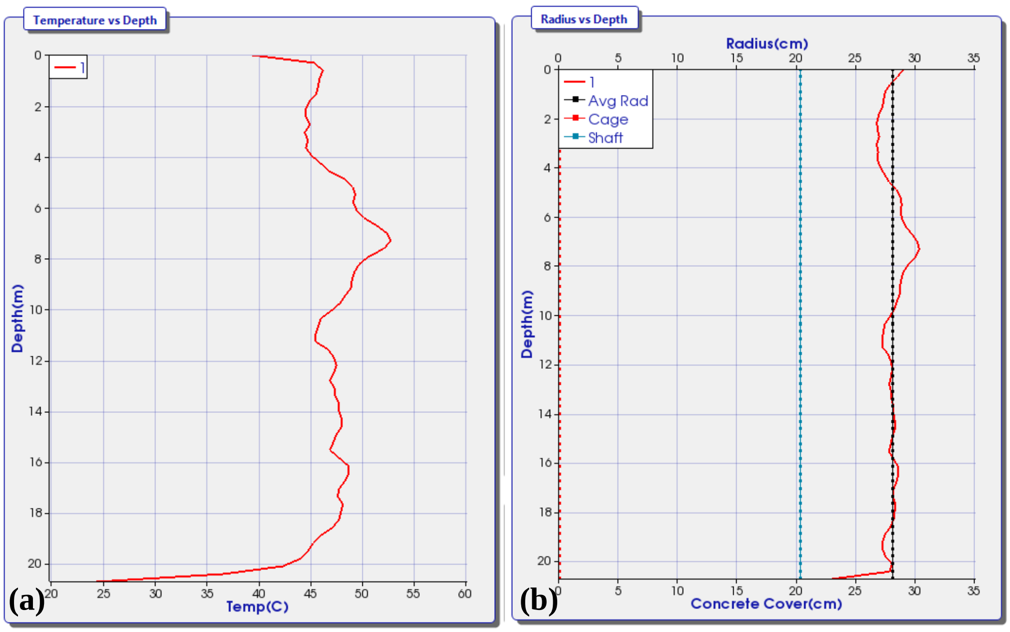

FIG 17: (a) Temperature vs. Depth and (b) Radius vs. Depth: Pile A-2

Pile A-2, was also analyzed in the same manner. Figure 17a is the peak temperature profile for this pile, and shows a larger variation in temperature. Installation logs confirmed additional grout placement at the upper middle portion of this pile where higher temperature measurements are indicated. From the temperature profile and installation logs, an effective radius was determined and is shown in Fig 17b. As with the previous pile, Pile A-2 illustrates a heat signature of a good quality pile throughout the profile.

Comparison with PIT and Dynamic Load Test Records

Separate low strain integrity testing was performed to compare with TIP results for several ACIP piles. In addition, the selected piles were already specified for dynamic load testing, therefore at Unit 1, a 1.5-m (5-ft) long casing and buildup was added to the original pile length of 22.3-m (73-ft). This additional section was constructed after TIP was performed, such that the total pile length for low strain integrity testing and dynamic load testing was 23.8-m (78-ft).

For this pile length and diameter, the L/D ratio is 52, which is beyond the normal limits of PIT reliability. Most piles lacked clear toe reflections. However, test pile A-3 may present the best complete pile reflection and a PIT record for this pile is shown in Fig. 18. From the velocity wave reflections, a bulge is located in the mid-upper section with reduced area below, and a possible toe reflection at 23.8-m (78-ft).

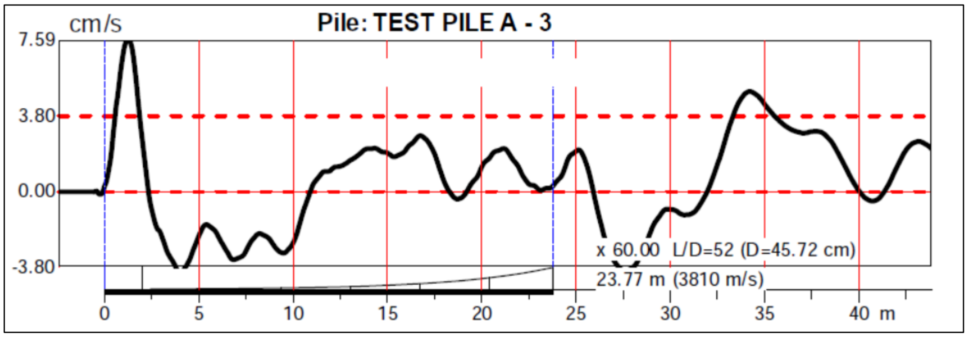

FIG 18: PIT Record: Test Pile A-3

Grout installation logs were used to compare with PIT impedance reflections. The top 1.5-m (5-ft) of this test pile has a fixed 45.7-cm (18-in) radius due to casing. Below this, 130% of the theoretical concrete volume is in the top 9.1-m (30-ft), with 150% in the next 7.6-m (25-ft). The remaining pile length contains around 110% of the theoretical volume. Aided by these logs, a profile was generated from the PIT record from Test Pile A-3, independent of the TIP results. The PIT profile would generally confirm the TIP effective radius vs depth results (Fig. 19).

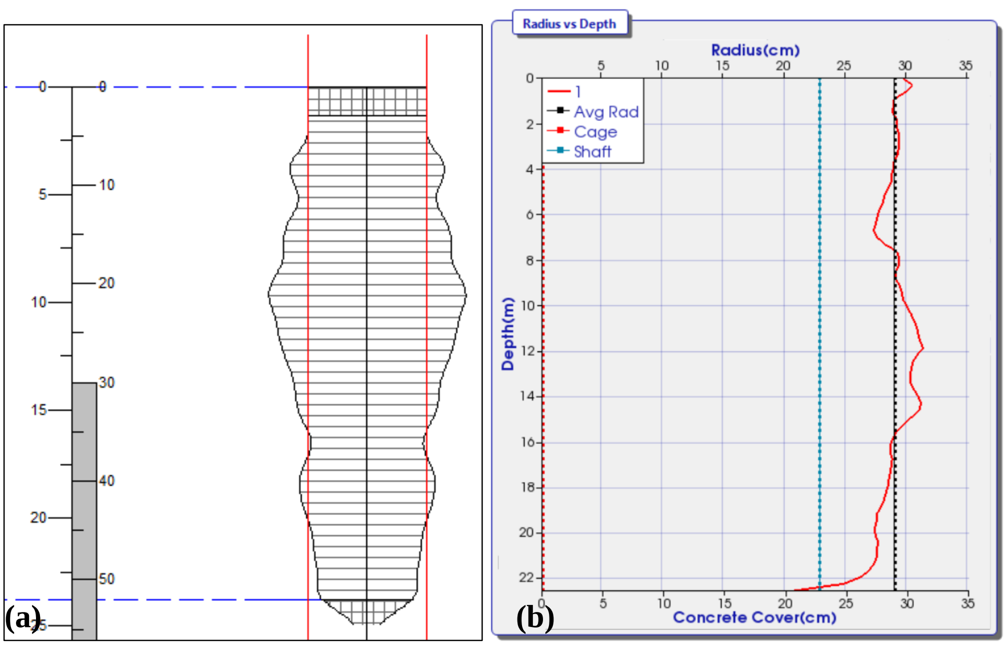

FIG 19: (a) PIT Profile and (b) TIP Radius vs. Depth: Test Pile A-3

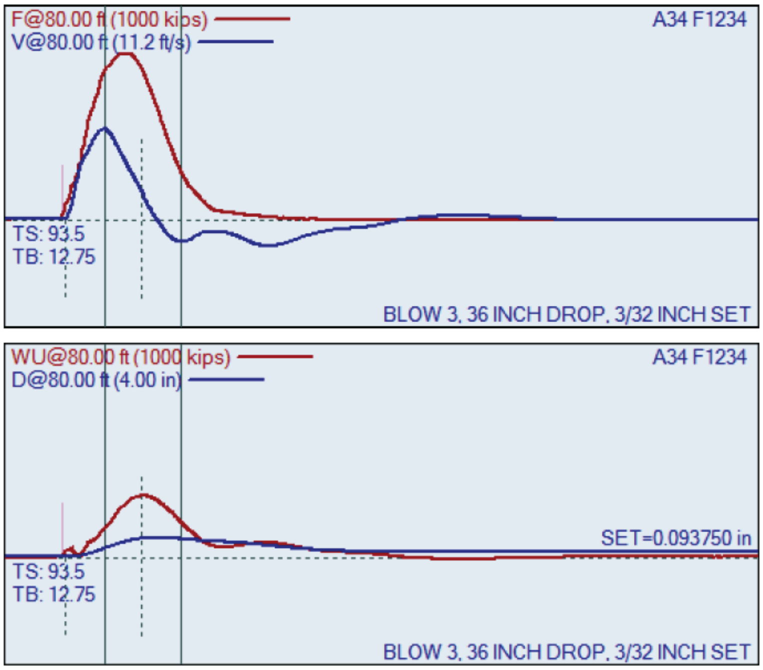

FIG 20: Dynamic Load Test Record: Test Pile A-3

Dynamic load test results also confirmed good quality pile integrity. A continuous pile is indicated as no major inflections in the force or velocity occur until the expected pile toe location (Fig 20). A CAPWAP was performed on this dynamic load test record, and impedance was modified to more accurately reflect the pile shape. The comparison between CAPWAP impedance and TIP results are shown in Fig 21.

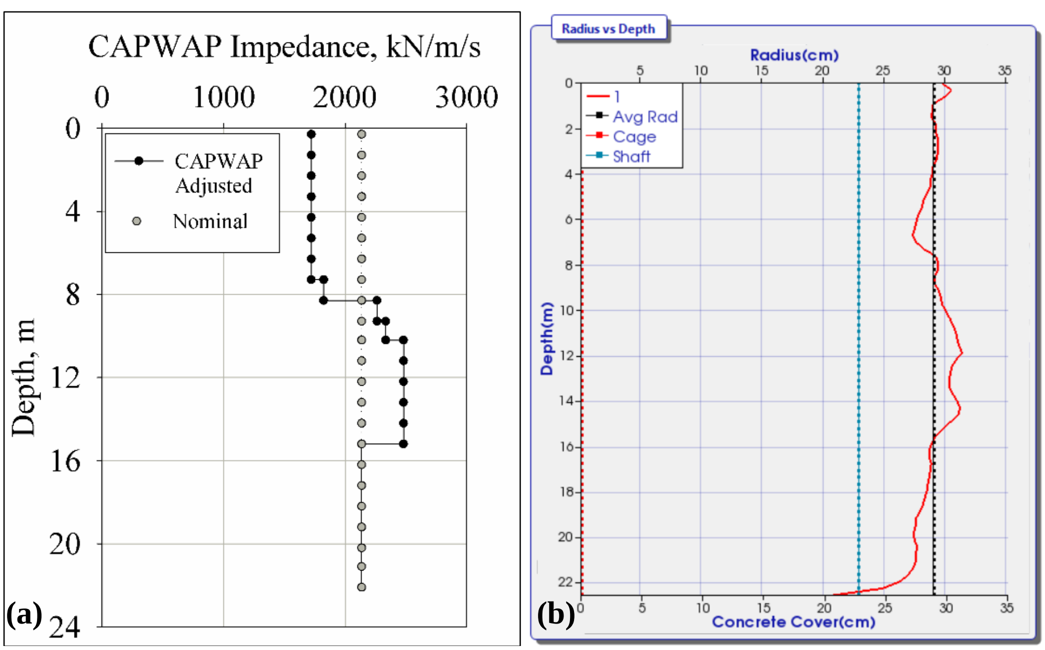

FIG 21: (a) CAPWAP Impedance and (b) TIP Radius vs. Depth: Test Pile A-3

A radius increase is apparent in the middle section of both the PIT and TIP radius profiles, and parallels with the impedance increase via CAPWAP. Indicated in the lower section of the PIT profile, the pile radius is about equal to the theoretical radius, as well as the CAPWAP nominal and adjusted impedance. The TIP profile shows a slight radius decrease from the middle section down and thus, also relates well. After comparing the PIT Profile, CAPWAP impedance and grout installation log to the thermal profile, confidence may be gained when using a single temperature cable for TIP.

CONCLUSIONS

For the referenced project, TIP proved to be an acceptable and advantageous integrity test method. Due to the number of foundation elements, performing this test allowed for an accelerated integrity analysis, thus reducing contractor idle time while waiting for pile acceptance. On-site engineering time was reduced since, after training, the inspection agency was able to attach the temperature cable, connect data collection units and send data via email once collected.

Thermal integrity profiling was chosen over pulse echo testing and SSL. The foundation L/D ratio was above the recommended reliability range for pulse echo testing, while SSL would involve casting in many access tubes and waiting for curing to complete. Both would also require significant on-site engineering time to perform the number of tests required. Moreover, TIP provided for less engineering on-site time, reduced installation to analysis and reporting time and showed a complete pile profile more reliably.

Of the 444 total ACIP piles, half were instrumented, while 20% of the total were randomly selected for analysis. For these 45.7-cm (18-in) diameter piles, data collection continued approximately 24 hours after installation, and was then sent in for analysis.

Some instrumented piles showed irretrievable data (i.e. loss of single temperature node, damage of entire cable, faulty data collection unit, etc.). Only a single centralizer was used on the center rebar, and it was not in the vicinity of the reinforcing cage. Since functionality was inspected prior to placement, sensor or cable damage likely occurred during either center bar insertion, or when the reinforcing cage was positioned around the center bar. In the future, additional centralizers may be useful to prevent possible cage shifts into the center rebar during insertion.

Comparisons of thermal profiles to grout installation logs were consistent, although the total volume of concrete is factored into the TIP Reporter program. The pulse echo test and CAPWAP adjusted impedance presented encouraging results as the pile profile via PIT, TIP, CAPWAP impedance and grout logs were similar. Unfortunately, few piles were tested with PIT, and the majority tested in this manner did not show a clear pile toe.

For this project, the TIP testing process was performed with relatively few issues, while good rapport was sustained between all parties involved. For future projects, this communication is vital for a successful test program, as the responsible engineer may require grout logs, site condition descriptions, and details of installation issues, while the contractor should be properly informed of any installation and/or data collection techniques. Although this is a relatively new integrity test method for ACIP piles, thermal integrity profiling with a single temperature cable was completed with acceptable results, while future projects will supplement the knowledge and confidence gained herein.

ACKNOWLEGDEMENTS

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