Using Thermal Integrity Profiling to Confirm the Structural Integrity of foundation applications

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Abstract

Quality of cast-in-place foundation applications, including Augered-Cast-in-Place (ACIP) piles and Drilled Shafts (particularly those cast under slurry) is greatly dependent upon the practices of the site personnel. Due to the installation techniques used to install these elements, it is usually not possible to inspect the hole through any Non-Destructive Test (NDT) method prior to grout or concrete placement, but there are several NDT methods available to indirectly assess the integrity of these completed elements. This paper will compare several NDT methods with the method of Thermal Integrity Profiling (TIP) for confirming integrity in ACIP piles and drilled shafts. The TIP method evaluates the integrity over 100% of the element cross section by measuring the hydration temperature during the early curing of the grout/concrete along the length of the element. The temperature measurements are typically concluded within 4 to 48 hours after placement, thus accelerating construction. For the generally small diameter ACIP piles, meaningful measurements often can be at as little as 4 to 8 hours after casting. The use of TIP in ACIP piles and Drilled Shafts can effectively overcome several limitations inherent in other NDT methods. Thermal Integrity Profiling will be described and several examples will be presented where TIP testing was used to confirm the structural integrity of ACIP piles and Drilled Shafts.

Introduction

Drilled shafts can be a desirable foundation element in many applications due to the large axial and lateral capacities which are attainable for very large drilled shafts. Drilled shafts cast in a dry hole allow for inspection of the hole prior to casting, but the casting process is very difficult to inspect with any accuracy. Drilled shafts are often cast under slurry as a means to stabilize the surrounding soils during the construction process. When casting under slurry, it is very difficult to nearly impossible to inspect the hole prior to casting and it is equally difficult to inspect the shaft during the casting process. Augered-Cast-in Place (ACIP) piles are an attractive foundation choice due to their relative ease and speed of installation. The trend has been to use larger ACIP piles carrying greater loads to support ever more important structures, which makes quality control ever more critical for these piles. The above mentioned processes are typically blind to inspection and therefore the foundation integrity is often unknown, adding risk to the process. A failed foundation due to construction defects results in disproportionately large remediation costs or in extreme cases the demolition of the supported structure.

There are several Non Destructive Test (NDT) methods available for integrity testing of completed elements. Each of these methods has advantages and limitations (White et al, 2008). Some methods test the integrity within a small proximity of an access tube while others test the shaft core but do not test the region outside the reinforcing cage (i.e., concrete cover). The Thermal Integrity Profiling (TIP) NDT method overcomes many of the limitations associated with other NDT methods. This TIP method involves measuring the heat generated in the foundation element during the hydration process to determine the pile integrity.

The TIP method evaluates the entire cross-section of the foundation element under test, along the entire shaft length, allowing for evaluation of concrete cover in addition to the shaft core. Pile length to diameter ratios, or non-uniform shapes that can occur by design or unintentionally during the construction process, which can restrict pulse-echo integrity testing methods, are not a restriction to the TIP method. This paper will discuss the current state-of-practice for integrity testing of drilled shafts and ACIP piles and will detail application of this TIP method.

Current Shaft Integrity Testing Methods

Typical integrity test methods currently utilized for drilled shafts and ACIP piles include the low strain pile integrity testing (pulse-echo) and the cross hole (or single hole) ultra-sonic testing. The low strain pile integrity test method involves attaching an accelerometer to the pile top (typically using a putty or wax) and striking the pile top surface with a small handheld hammer. The hammer strike creates a compressive wave within the pile which will reflect off the pile toe and return to the pile top where this return signal is measured by the accelerometer. Changes in the pile cross-section (necking or bulging) will also cause a reflection of the input compressive wave and these additional reflected waves will be measured by the accelerometer on the pile top at a time earlier than the expected pile toe reflection. This low strain integrity test is generally limited to revealing *major* defects within a pile. This test is very fast and economical, requiring no special construction techniques (no access tubes required, etc.). One individual can test any or all piles on a site, with many piles typically tested in one day. However, non-uniformities cause reflections which complicate data interpretation. Larger bulges located near the pile top create multiple reflections which make it difficult or impossible to assess the integrity of the shaft below this point, casting doubt on the pile because of the inconclusive test even though the pile is structurally sound. As the length to diameter ratio increases beyond 20 to even 50 (depending on the pile uniformity and soil strength), it can be increasingly difficult to get a reflection from the pile toe, thus leaving the lower section of the pile potentially untested. Site vibrations or reinforcing bars which extend significantly above the pile top can cause extra vibrations that may interfere with the test signals.

The Cross Hole Sonic Logging (CSL) or Single Hole Sonic Logging (SSL) test requires that access tubes be installed in the shaft prior to casting. If the access tubes are not planned prior to construction, the test cannot be conducted. For the CSL test, steel or plastic pipes of typically 2 inch (51mm) diameter are cast into the shaft and immediately filled with water upon completion of the shaft. For CSL testing, steel access pipes are preferred as they are less likely to de-bond with the concrete as compared to plastic access pipes. The CSL test entails inserting an ultrasonic transmitter into one access tube and a receiver into another access tube. The transmitter and receiver are lowered to the bottom of the tubes and raised together, generally keeping the transmitter and receiver parallel to one another, and pulses from the transmitter are recorded by the receiver typically every 2 inches (50 mm). Knowing the spacing between tubes, the arrival times for the received signals are converted to wave speed (tube spacing is assumed to be constant throughout the length of the shaft). Delay in signal arrival time between the probes results in a lower wave speed and corresponds to weaker concrete. The CSL test is limited in that it only assesses concrete quality between the access tubes, thus evaluating concrete only within the reinforcing cage and providing no information outside the reinforcing cage (concrete cover is unknown). Scanning all access tube combinations provides a fairly accurate assessment of the pile core but cannot scan the region outside the access tubes. Thus the concrete cover cannot be evaluated with the CSL method. For smaller diameter ACIP piles with only a single center reinforcing bar a single access tube can be installed and both receiver and transmitter installed in the same tube with a fixed separation between probes being greater than one pile diameter. In the author’s experience, the SSL test will only detect defects which cover the full cross section.

Each of the above mentioned test methods can help determine the integrity of drilled shafts and ACIP piles but, as noted in the previous text, each test method also has limitations associated with it. The TIP method has the ability to overcome many of the limitations of these other test methods.

Thermal Integrity Profiling

The Thermal Integrity Profiling (TIP) method determines the integrity of a shaft both inside and outside the reinforcing cage by measuring the hydration temperature of the concrete along the length of the shaft. The temperature measurements are made by embedding a THERMAL WIRE® cable within the shaft. Temperature measurements at the various measuring locations in each cross section and at periodic depth intervals, along with the total concrete volume data are used to determine the shape of the shaft.

Curing concrete exhibits a normal heat signature dependent upon the shaft diameter, concrete mix design, concrete quality, and soil conditions. A local reduction in cement content in the concrete (defect) will interrupt the normal temperature signature in the area of the defect. This defect will also be seen in adjacent measurement locations; however the effect at these more distant measurement points is reduced. Any temperature measurements which are cooler than the average are areas of reduced concrete volume (defect) or poor concrete quality and any area with a higher temperature than the average are areas of increased concrete volume (bulge). The severe local reduction in temperature shown in Figure 1 located at depths approximately 20, and 47 feet below the top of shaft indicates a defect at these locations.

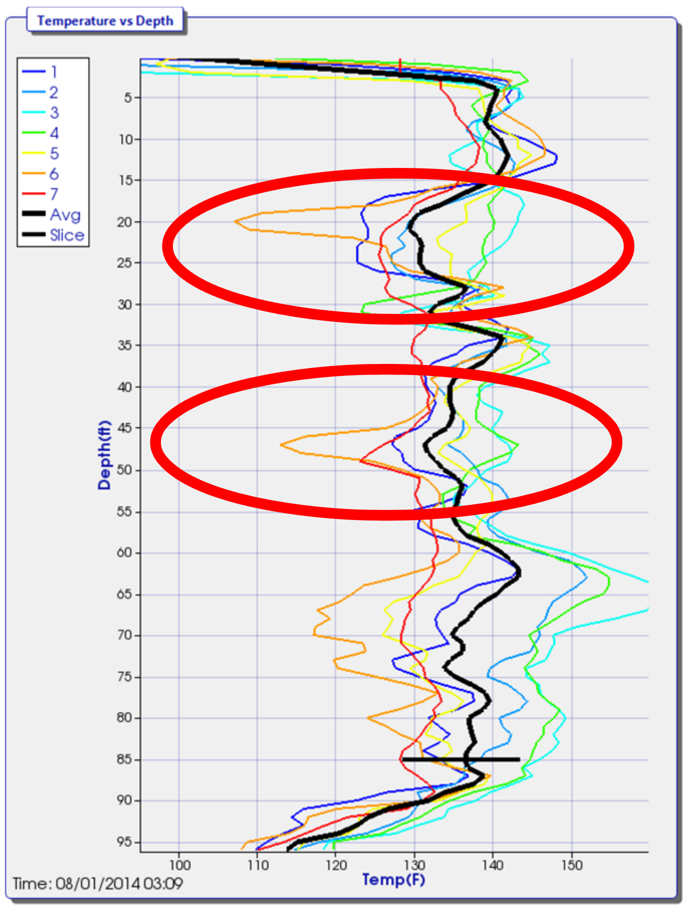

Figure 1. Thermal results showing defects at various locations

In addition to determining shaft integrity, the TIP test will also reveal any potential issues with reinforcing cage alignment. When comparing temperature measurements from diametrically opposite locations versus the average value, the cage alignment can be determined. If one location is cooler than the average and the diametrically opposite location is warmer than average it indicates that the cage is not centered. The cooler measurements indicate a location shifted towards the soil interface while the warmer measurements indicate a location shifted towards the shaft center. This can be seen in figure 1 at a depth of approximately 60 to 75 feet, where wires 5, 6, 7 are cooler than the average and their diametrically opposite pairs consisting of wires 2, 3, 4 are warmer than average.

This cage alignment analysis provides additional information on concrete cover, which can be reduced even without having a defect present. In the example shown in Figure 2, location 5A is warmer than average throughout the length of the shaft while diametrically opposite location 1A is cooler than average, so it can be determined that the cage is shifted such that location 5A is closer to the shaft center and location 1A is closer to the surrounding soil (reduction of cover at location 1A).

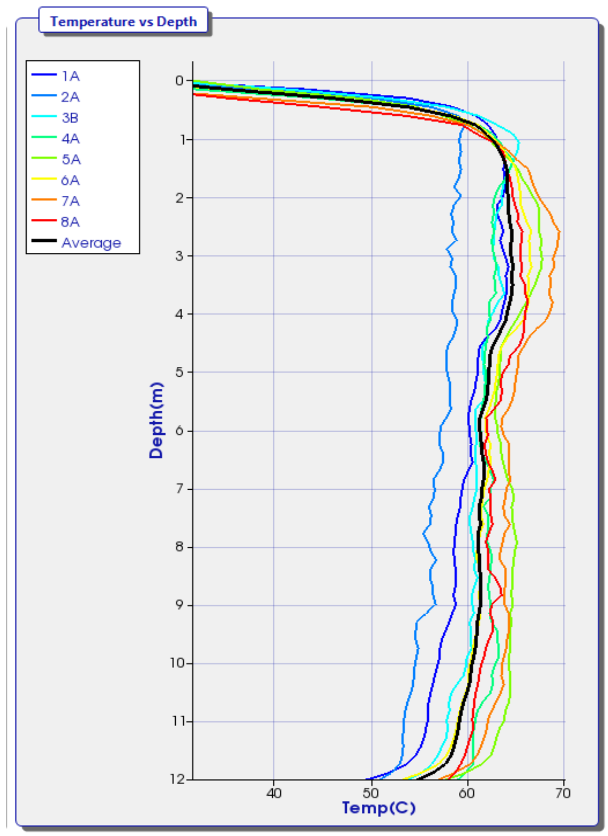

Figure 2. Thermal results showing cage offset

It is recommended to have one measuring location (e.g. THERMAL WIRE cable) per foot of shaft diameter (e.g. 10 THERMAL WIRE cables installed for a 10 foot diameter shaft) and spaced approximately equidistantly around the reinforcing cage perimeter. Anomalies greater than 10% of the cross-sectional area will be detected by multiple measuring locations. Anomalies smaller than 10% of cross-sectional area will generally be detected only at the nearest measuring location, but these small anomalies are typically relatively insignificant and the shaft might still be used considering a reduced structural strength (O'Neill and Sarhan, 2004).

Along the shaft the heat transfer is basically radial. However at the top and bottom of shaft the heat transfer is also longitudinal, producing a reduction or "roll off" in a thermal integrity profile having a hyperbolic tangent shape. Observing this natural roll off at the bottom confirms the shaft length. Knowing this characteristic roll off shape allows for a top and bottom of shaft correction to be applied to the recorded thermal measurements. If the measured roll off in temperature fits a hyperbolic tangent curve, then the shaft has no anomaly and is cylindrical in shape. If the hyperbolic tangent curve does not match the measurements, then an anomaly is indicated.

Temperatures during the concrete hydration process are measured by embedding temperature cables into the shaft. These temperature cables are placed equidistantly around the reinforcing cage, and are quickly attached via zip ties to the longitudinal rebar members of the reinforcing cage. The thermal measurements are taken automatically at regular time intervals (typically every 15 minutes) generally at least until the shaft has reached its peak temperature. The temperature at each location can be scanned for local reductions in temperature (e.g. defects or poor quality concrete lacking cement content) at any time during the curing process. Defects are best observed during the early curing stage, well before the peak temperature. Using the concrete volume installation records, the average recorded temperature is equated to the average radius (which is determined from the known length and the total measured volume). Once this average temperature to average effective radius correlation has been established, the effective radius at all points along the shaft can be calculated. When the individual temperature measurement is lower than the overall average, a reduction of cover is indicated. Similarly, when any temperature measurement is higher than the average, the increase in cover (bulge) can be determined.

Table 1 summarizes the various phenomena that are determined with the TIP method along with the interpretation method used to make such determinations.

Table 1. TIP detection and Interpretation Method

TIP Detection	Interpretation Method
Shape of Shaft	Average temperature reveals overall shape of the shaft
Bulge	Localized temperature increase
Defect/Necking	Localized temperature decrease
Poor Concrete Quality	Localized temperature decrease
Cage Alignment	Compare diametrically opposite thermal measurements
Concrete Cover	Local temperature measurements compared with overall average temperature measurement combined with total volume placed
Soft Bottom	Inability to properly correct the bottom roll-off with hyperbolic tangent function
Cage terminating above shaft bottom	No bottom roll-off observed in thermal data
Shaft Radius at any location	Local temperature measurement compared with overall average temperature measurement combined with total volume placed

The evaluation of any shaft using any NDT method should include consideration of the subsurface conditions, construction records, and site observations. In making an assessment of the shaft geometry with TIP, it is important to consider the site and soil conditions, as certain conditions such as flowing river water or flowing groundwater can remove heat from the hydrating cement at a higher rate than what would occur in a more stable subsurface environment.

Drilled Shaft Example

TIP testing was performed on the test shaft for the Jet Monorail project in Jakarta, Indonesia. In addition to the TIP test, CSL and PIT were also performed. The test shaft is 98.4’ (30m) long and 4.9’ (1.5m) in diameter. There were four TIP wires installed in the shaft. The TIP testing began immediately upon completion of concreting the shaft.

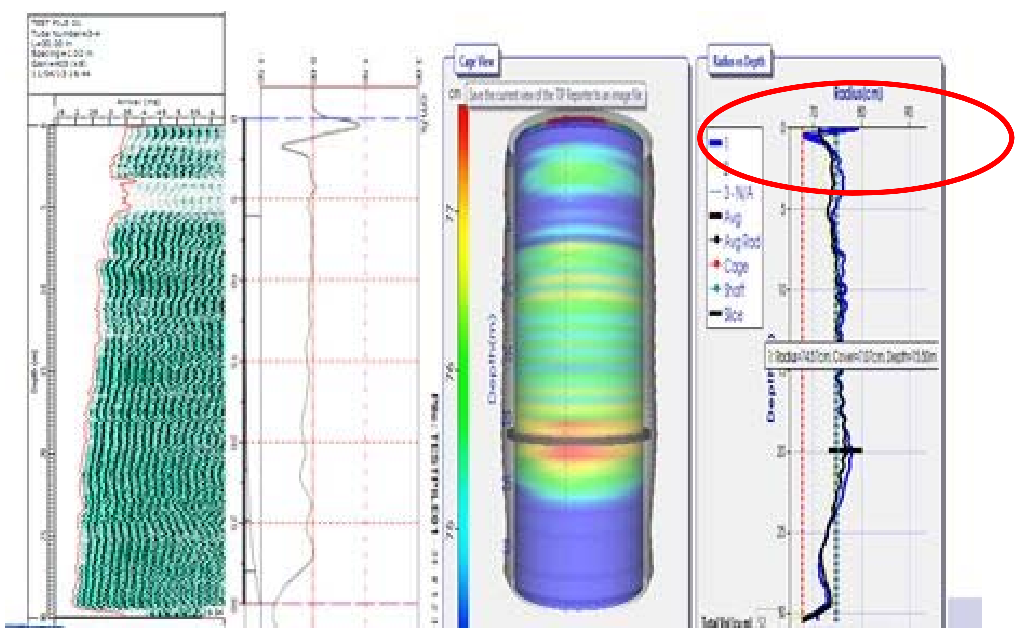

Figure 3 CSL left, PIT canter, TIP right

The TIP test results indicated a sharp temperature reduction (severe defect) less than 1m below the pile top (circled section in Figure 3). Six days after the completion of the shaft, PIT and CSL testing were performed. Several hammer sizes were used in multiple locations around the pile top, but the PIT test was unable to identify a defect less than 1 m below the pile top. Similarly, the CSL test was conducted and the results also failed to identify the defect less than 1 m below the pile top. The TIP, PIT, and CSL results are shown in Figure 3. From the TIP results, a clear reduction in temperature can be seen less than 1 m below the pile top surface. After reviewing all NDT results, since the suspected defect indicated in the TIP record was very close to the ground surface, the pile top was excavated. Upon excavating to less than 1 m below the ground surface, the defect was clearly visible (Figure 4), confirming the TIP results. The defect was repaired, saving the project from a potentially costly foundation failure. TIP was then used on additional shafts as an integral part of the NDT program for this project.

Figure 4. Excavated shaft

ACIP Pile Example

TIP testing was performed on ACIP piles installed on a project in southern Indiana. The piles were 73’ (22.3m) in length and 18” (450mm) in diameter. The TIP cable was tied to the center reinforcing bar. The soil conditions consisted of stiff clay to approximate depth of 30 feet (9.1m) underlain by sand below 30 feet (9.1m). The testing initially included both PIT and TIP for the test piles. The ACIP piles were typically irregular in shape with bulging occurring near the surface as well as about 30 feet (9.1m) below the surface where the sand layer begins. The irregular pile shape makes the PIT analysis difficult, and in some cases it was not possible to see a clear toe reflection with PIT as shown in Figure 5.

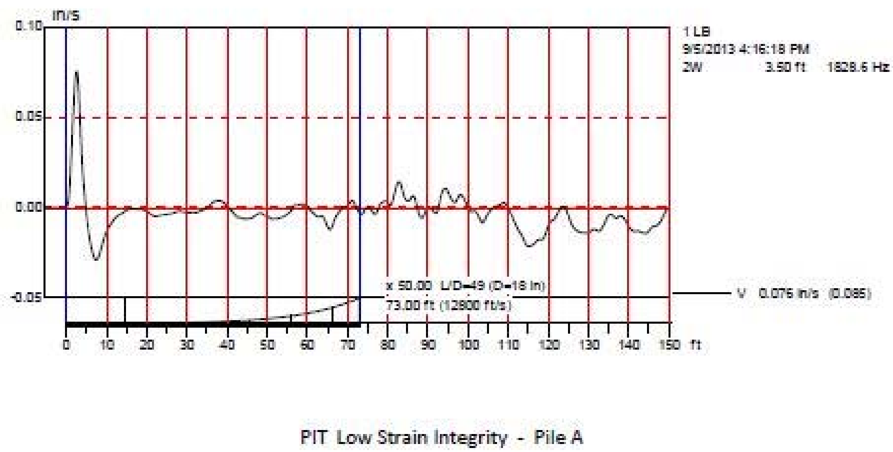

Figure 5. PIT results

The TIP results for the same pile are shown in Figure 6. TIP clearly shows a bulge near the surface, but the remainder of the pile is easily evaluated despite the upper bulge, and no sharp local significant reduction in temperature was noted. TIP results show an additional bulge at 30' (9.1m) where the soil conditions change from clay to sand. These results from TIP were typical for other piles on this project and allowed the acceptance of these ACIP piles, where PIT testing would have yielded unknown results. After the initial testing on this project, TIP was accepted as the primary quality assurance method and was successfully performed on 50% of the 442 production piles. Unlike low strain PIT testing, TIP has no limitation on depth.

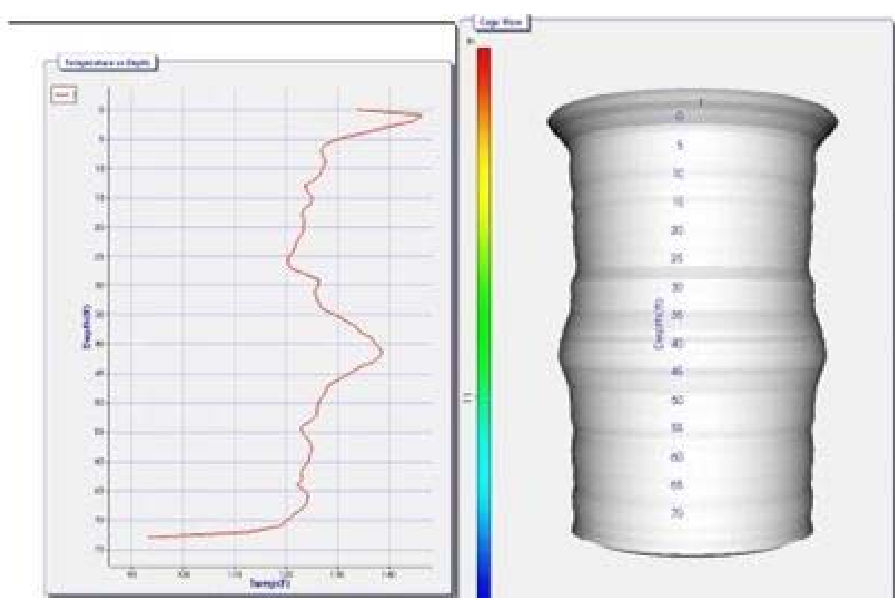

Figure 6. TIP results with 3-D image on right

Conclusions

The general deep foundation industry trend has been an increase in the use of drilled shafts and ACIP piles. These piles are often installed with little or no knowledge of the final shaft integrity, and to minimize concerns and reduce risk of failure, NDT methods are usually employed to investigate their structural integrity. Many common current NDT methods can each provide partial information as to shaft integrity, but each method also has limitations. The TIP method measures the shaft temperature during the hydration process to make an assessment of the shaft integrity. From these temperature measurements, the effective shaft radius can be estimated. TIP method allows for 100% assessment of the shaft cross-section, including concrete cover and cage alignment, which no other current method can provide. Additionally, the cage alignment can be investigated and the concrete cover evaluated from the TIP data. Frequently the results of the TIP test are completed within 4 to 48 hours after the shaft has been cast, which is a major advantage over current methods as this can accelerate the construction process.

As shown from the included examples, TIP can effectively locate defects within a shaft and can further confirm the integrity of ACIP piles including those with bulges which often render low strain PIT testing inconclusive. The ACIP pile example shows that PIT had limitations in the test due to the large length to diameter ratio and non-uniform pile shape which made interpretation impossible while TIP easily confirmed lack of defects and therefore the integrity of the ACIP pile in question. Many field tests have been successfully conducted and comparisons have been made with other available methods. Unlike other current NDT methods which provide limited shaft integrity information, the TIP method evaluates the shaft integrity without the limitations associated with other methods.

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