Transmission Pier Foundation QC/QA

Gina Beim, P.E., M.ASCE[1]; Robert Kluge, P.E.[2]; Matthew Lohry, P.E.[3]; and Daniel Belardo[4]

[1]Pile Dynamics, Inc., 30725 Aurora Rd., Cleveland, OH 44139. E-mail: gbeim@pile.com

[2]American Transmission Co., 5303 Fen Oak Dr., Madison, WI 53718. E-mail: rkluge@atcllc.com

[3]American Transmission Co., W234 N2000 Ridgeview Parkway Ct., Waukesha, WI 53187. E-mail: mlohry@atcllc.com

[4]GRL Engineers, Inc., Central Office, 30725 Aurora Rd., Cleveland, OH 44139. E-mail: dbelardo@GRLengineers.com

Abstract

Transmission line foundations often consist of concrete piers. Examples of construction situations that may result in problematic piers are presented to motivate the use of deep foundation non-destructive testing methods. Advantages and shortcomings of established testing methods are briefly reviewed. A newer technology, Thermal Integrity Profiling (TIP), is then discussed and compared with established ones. TIP is based on the premise that heat energy released during cement hydration depends on cement content and on total concrete volume. Temperature measurements obtained inside a curing foundation correlate with the effective radius of the foundation and with concrete quality. The theoretical background of thermal integrity profiling is summarized; descriptions of alternate ways of obtaining internal temperature measurements follow. Measurement interpretation is discussed, including relating data measured at the reinforcement cage during curing to concrete quality, shaft diameters, local concrete cover, and reinforcement cage alignment. Case studies of electrical transmission line construction where this technology was employed are presented.

INTRODUCTION

Transmission lines are often constructed with tubular steel poles. These poles are generally direct buried or mounted on concrete pier (caisson) foundations, although a small percentage are mounted on driven piles or helical foundations. Pier foundations (also called drilled shafts) are often specified for the most critical and heavily loaded structures such as at dead-end and large angle applications or where the soils are weak or saturated (the excavation extends below the water table). It is precisely on these critical pier foundations that the engineer needs assurance that the structural element is sound and possesses all the intended design attributes.

In this paper, we discuss procedures to increase the confidence on the integrity of the installed shafts. We review quality control (QC) measures to be utilized before and during construction, including examples of what can go wrong even when highly qualified workers and QC measures are employed, and discuss quality assurance

(QA) utilizing non-destructive evaluation (NDE). We compare various NDE methods relative to difficulty of deployment and effectiveness in discovering defects. We suggest that planning ahead for NDE may circumvent potential impacts on project cost and schedule. We then present a relatively new NDE method – Thermal Integrity Profiling – along with case studies where it has been utilized on electrical transmission line projects.

Quality Control Measures Prior to and During Construction

Quality control measures taken before and during construction are extremely important, along with thorough documentation of observations and test results.

Good practices in preparation for a foundation project include ensuring clear and concise specifications and design drawings; trained and qualified workers and inspectors; accurate preliminary site investigations and soil borings; well thought out work plans and well laid out work sites; a pre-approved concrete mix design appropriate to the site and foundation, and preparation for concrete field sampling and testing and for non-destructive testing.

In spite of good preparation, a myriad of mistakes may happen during foundation construction, among them several that may cause defects. Reinforcement cages may not meet specifications, may have insufficient bracing to be lifted safely, may not maintain their shape during placement or may not be properly centered in the excavation to provide concrete cover. Excavated soils may not match the soil boring at the location. The delivered concrete may be inadequate, or its delivery time may be excessive. Free-falling concrete may strike the reinforcing cage or may not flow freely through the rebar cage to the perimeter of the excavation. Tremie or pumping tubes may be mishandled. Proper measures may not be taken when concrete placement is arrested for an extended time. The excavation may blow up or cave in, and soil may drop into the hole for a variety of reasons. Figure 1 shows a form placed above ground for the foundation reveal. Soil placed around the form fell under the form and against the reinforcing cage creating a large void at ground level and exposing the reinforcing steel to corrosion.

Figure 1. Fill placed around and pushed under top form created a void at ground level

Mullins and Ashmawy (2005) reported to the Florida Department of Transportation about various causes of anomalies in drilled shafts. Quality workmanship and inspection reduce the incidence of anomalies. However, regardless of how diligent the team is, they cannot possibly observe what is happening during the excavation or concrete placement in a submerged hole that is filled with water or slurry. Even on a dry shaft, with visual inspection it is impossible to evaluate the conditions beneath the surface of the placed concrete. However, it is primarily for these water-submerged excavations that a means to evaluate the integrity of the as-built foundation is imperative, and the need to deploy non-destructive testing arises.

Admittedly, the transportation industry has historically adopted foundation quality control methods before any other industry. Even though testing programs may not be as commonly used in electrical transmission lines as they are on bridge foundations, traditional integrity testing methods have been employed. In the next section, we discuss these methods, their advantages, and their limitations.

CAST-IN-PLACE FOUNDATION INTEGRITY: TRADITIONAL METHODS

Traditional nondestructive integrity testing methods for cast-in-place concrete foundation include the low strain (pulse echo) pile integrity tests, cross-hole sonic logging (CSL), and gamma-gamma logging (GGL). A brief description of each follows; Rausche (2004) presents a lengthier overview of each. If no provisions are made before the concrete is placed to conduct integrity testing, the options are limited to low strain pile integrity tests or core drilling. Core drilling is typically not considered a test, but an exploratory method. In transmission tower foundations in particular, it is difficult to execute because of insufficient space between the anchor bolts and the rebar cage, causing the drill to strike the steel construction bracing. Because of the cost and difficulty, core-boring has been selectively deployed only when and where problems were suspected.

Low strain integrity tests consist of impacting the shaft with a hand-held hammer to generate a compressive wave that reflects off the toe of the foundation and returns to the top, where the return signal is measured. Changes in cross-section will also cause reflection, albeit an earlier than expected one. It is therefore possible, in ideal circumstances, to observe major defects within the foundation. Although the test is fast and requires no special construction techniques, it may be inconclusive for shafts with large length- to- diameter ratios, which are typical in transmission lines

CSL requires that access tubes be placed into the shaft prior to casting (typically attached to the reinforcing cage). After curing, an ultrasonic transmitter is inserted into one of the tubes and a receiver into another. The transmitter and receiver are lowered into the foundation and lifted back up; the received signals are recorded and analyzed for their arrival times and energy. Signal energy and travel time from transmitter to receiver correlate with concrete quality and with the presence of anomalies within the perimeter formed by the access tubes. Scanning all access tube combinations provides a fairly detailed evaluation of the shape and location of a defect. However, CSL only assesses the central portion of the shaft, not the area outside of the reinforcing cage or of the concrete cover.

GGL is also performed through access tubes. A probe containing radioactive material is lowered into a tube as it emits particles that travel through the concrete to a photon counter. The counter determines the density of the material through which the particles passed. GGL scans a radius of about 76 mm (3 in) around each access tube, typically a very small percentage of the cross sectional area. When used together with CSL, it increases the test area beyond the perimeter formed by the tubes.

Each of these methods may be successful in evaluating the integrity of a shaft, but all have limitations. Performing more than one test may overcome these limitations.

THERMAL INTEGRITY PROFILING

Thermal Integrity Profiling is a relatively new (Mullins and Kranc, 2007; Piscsalko and Cotton, 2011) method that overcomes many of the limitations of NDE methods. It evaluates the concrete of all portions of the cross-section and along the entire length. It also assesses the positioning of the reinforcing cage and the concrete cover, and may be performed sooner than the other foundation integrity tests.

TIP consists of relating the temperature generated by curing cement to the quality of cast-in-place concrete foundations. In general, a shortage of competent concrete (necks or inclusions) is registered by relative cool regions; the presence of extra concrete (over-pour bulging into soft soil strata) is registered by relative warm regions. Anomalies both inside and outside the reinforcing cage not only disrupt the temperature signature near the anomaly, but also at more distant locations, albeit at progressively lesser effects.

The internal shaft temperature is dependent on shaft diameter, concrete mix design, and time of measurement. The theoretical temperature distribution within a perfect shaft is bell-shaped with respect to radial position. Temperatures measured within a shaft (typically at the reinforcement cage) skew away from the theoretical shape when the cage is eccentric or the concrete cover insufficient (Figure 2, Mullins, 2010).

A cage slightly closer to one side of the excavation exhibits cooler temperatures than average at measurement points closest to the soil, and warmer temperatures at measurement points closer to the shaft center.

In the region surrounding the cage where measurements are taken, temperatures vary linearly with shaft diameter. A plot of the average temperature from all measurement locations versus depth can therefore represent the actual shape of the shaft. The assessment of the overall shape and quality of the shaft is further improved by including construction and concreting logs in the analysis.

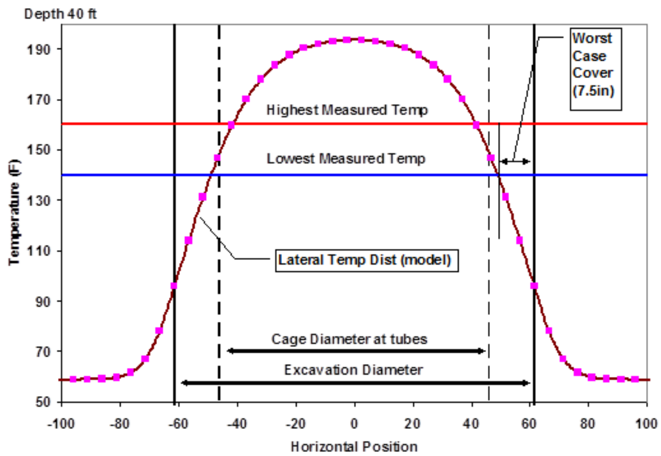

Figure 2. Distribution of temperatures measured inside a curing concrete shaft

ASTM (2014) provides procedures for measuring the temperature profile within cast-in-place deep foundation elements. Temperature measurements are obtained either by attaching cables fitted with digital thermal sensors to the reinforcing cage or by inserting probes into previously installed access tubes, similar to CSL or GGL (the probe method records temperatures along the length of the shaft, at the various tube locations, and at a moment in time during an optimal period of the curing process).

When data are obtained from cables (Figure 3), no access tubes are required. This is often advantageous for transmission line foundations where the geometry is such that installation of access tubes is challenging. Each of several cables within a shaft has thermal sensors at every 0.30 m (1 ft), and is outfitted with a battery-powered data acquisition unit that records temperatures at 15-minute intervals. The entire concrete curing process is monitored, and data are collected on site at any time after casting.

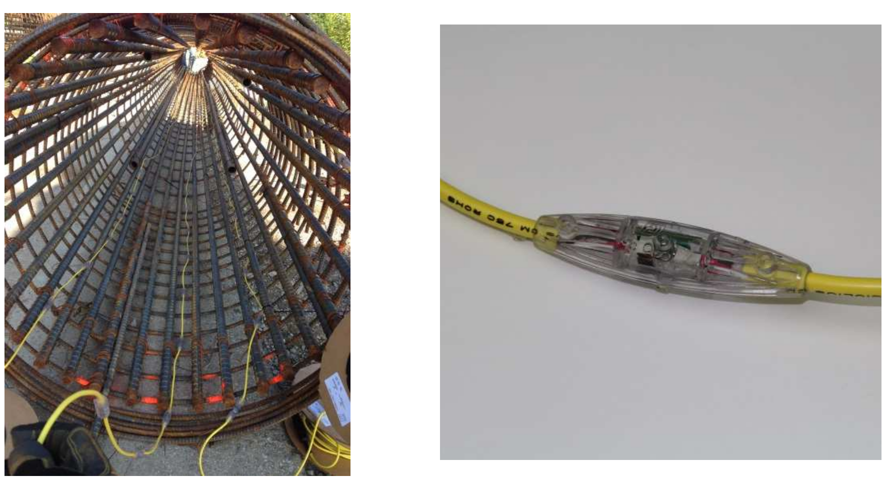

Figure 3. Cables with thermal sensors (detail right) attached to reinforcing cage

Temperature data collected and observed in the field may immediately highlight glaring irregularities. Because the average temperature profile shows the general shaft shape, observing how the temperature profiles measured at each point vary from the average of all profiles reveals cage misalignments, locations of potential bulges or necking, and areas of concern (Piscsalko et al, 2013).

Once information about concrete volume poured is obtained from field records, the actual effective radius at any location along the shaft can be estimated by equating the average temperature profile (usually near the time of peak temperature) to the average radius (computed from the total volume poured and total pile length). The term “effective radius” was coined to address the scenario where concrete quality may be varying instead of shaft shape. Effective radius is defined as the radius of intact uncompromised concrete that would produce the measured temperature.

Temperature data may be further evaluated for local defects. In this analysis, the temperature time history is searched (during the period well before the peak temperature is achieved) for local decreases in temperature which signal a reduced amount of heat-producing cement, either from necking (reduction) in the radius of the shaft or from contaminated concrete (by foreign material inclusion). Through a similar analysis, temperature increases signal a bulge in the shaft.

The temperature near the top of the measured profile typically exhibits a “roll-off” (cooling) effect due to heat radiating from the top of the shaft. Similarly, a temperature roll-off at the bottom is caused by heat exchange with the surrounding soil. It is relatively straightforward to distinguish these normal heat exchange effects from changes in temperatures caused by abnormalities in the shaft when the ambient and ground temperatures on site are known (and they typically are).

The next section presents Thermal Integrity Profiling case studies, discussing the methodology, as well as data interpretation, in more detail.

TIP CASE STUDIES

Projects A and B illustrate applications of TIP on drilled shafts designed to support transmission tower foundations. Project A exemplifies an intact shaft, while Project B showcases an instance of a defect. Both tests were performed by the cable method.

Project A

Project A, in southeast Wisconsin, consisted of a 3.20 m (10.5 ft) diameter, 13.4 m (44ft) long shaft (Table 1). Soil borings indicated stable in-situ soil conditions throughout the full length of the shaft. Ground water was encountered at a depth of 5.2 m (17 ft), and the excavation was subsequently filled with water to a height of 1.2 m (4 ft) below ground surface to increase pressure head. Data collection for TIP was initiated immediately after placement and was completed approximately 48 hours later when peak temperature was achieved.

Table 1. Project A Shaft Details

Planned Shaft Diameter	Reinforcing Cage Diameter	Observed Shaft Length	Theoretical Concrete Volume	Placed Concrete Volume
3.20 m (10.5 ft)	2.94 m (9.5 ft)	13.4 m (44 ft)	116 m^3 (152 yd^3)	130m^3 (170 yd^3)

In preparation for the test, the full length of reinforcing cage was instrumented with 10 Thermal Wire® brand cables evenly spaced around the circumference of the cage. Four temporary steel casings (also call liners) were installed in a telescoping manner along the full length of the excavated shaft prior to concrete placement. During installation, these casings were extracted when the concrete fill height reached the transition or overlap with the next casing located above. Concrete was fed into a hopper and placed via tremie method from approximately 4.6 m to 13.4 m (15 to 44 ft) and via free fall method from approximately 0 to 4.6 m. Concrete volumes and installation details were collected by an independent inspection firm.

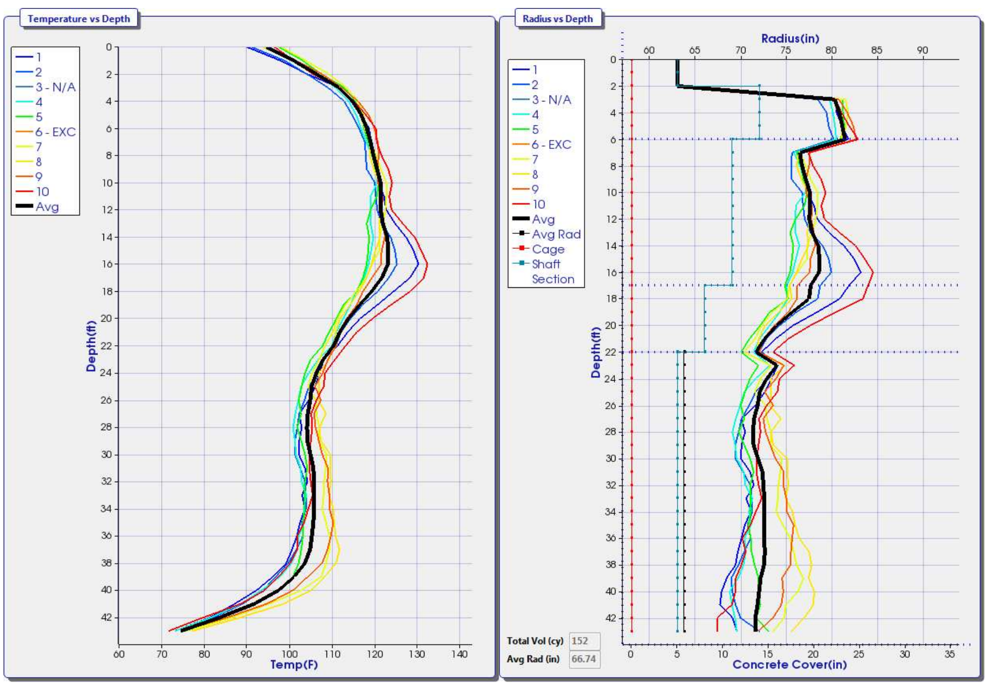

Figure 4. Project A Shaft: Measured Temperature versus Depth (left) and Estimated Radius versus Depth (right)

Figure 4 (left) is a plot of temperature measurements versus depth of each of the 10 cables, with the thicker black plot being the average of all 10. The right side of Figure 4 translates the measured temperatures into estimated effective radii versus depth and is obtained after measured concrete volumes are taken into consideration. The location (relative to North) of each of the 10 cables was noted prior to data collection.

Figure 4 shows a major bulge from 3.7 to 6.10 m (12 to 20 ft), with a maximum radius of 2.15 m (7 ft) on the northern face of the shaft. The location of this bulge corresponds to the depth where ground water was encountered. The reinforcing cage appears relatively centered to a depth of 8.5 m (28 ft) at which point there appears to be a minor shift to the base of the shaft as shown by the projection of the exterior relative to the cage. A normal temperature roll-off is observed at the top and bottom. The overall signature of the curve in the Temperature versus Depth graph and the integrity of the shaft appear suitable and as expected for the conditions encountered during installation.

A three dimensional (3-D) interpretation of the shaft (Figure 5) depicts the reinforcing cage as a two dimensional (2-D) color spectrum with an overlay of the projected shaft exterior surface.

Project B

Project B was also located in Wisconsin, however at a site remote from Project A. The shaft at Project B was drilled and placed by a different contractor from that of Project A. The soil profiles consisted of moist organic silt to a depth of 4.6 m (15 ft) underlain by silt to clayey sand to an approximate depth of 8.1 m (26.6 ft). Beneath this, limestone bedrock was present down to borehole termination at 10.4 m (34 ft).

The shaft diameter through the soil was 3 m (10 ft) from the top of shaft to a depth of 6.1 m (20 ft). The remainder of the shaft through the soil (6.1 to 8.1 m) and the rock socket (8.1 to 11.3 m) were 2.74 m (9 ft) in diameter. The 2.54 m- (8.3 ft)-diameter reinforcing cage was 11.1 m (36.5) long. The planned concrete cover was 0.10 m (4 in).

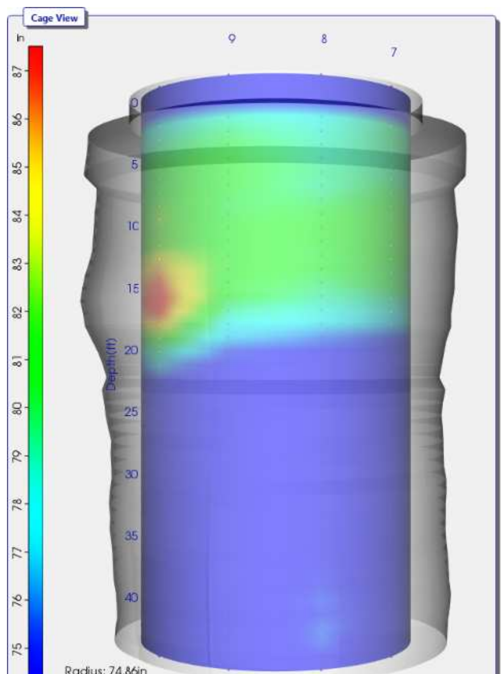

Figure 5. Project A Shaft: 3-D Interpretation

A permanent casing with an inside diameter of 3 m (10 ft) was reportedly vibrated into rock with an ending depth of 8.1 m (26.5 ft). The drill diameter down to 6.1 m (20 ft) was 3 m (10 ft). The drill diameter for the remainder of the shaft, down to 11.3 m (37 ft), was reportedly 2.74 m (9 ft). Based on the reported installation details, the bottom 2.0 m (6.5 ft) of the cased section may have contained 127 mm (5 in) of unexcavated soils around the inside of the casing. Water was reportedly introduced into the excavated shaft when the drill depth reached 5.5 m (18 ft).

In preparation for the TIP test, the reinforcing cage was instrumented along the full length with 10 Thermal Wire cables evenly spaced around the circumference of the cage. Concrete was fed into a hopper and placed via tremie method.

The tremie extended to the base of the shaft at the start of the pour. When the placed concrete reached 4.3 m (14 ft) below the top of shaft, a vacuum truck was used to extract the slurry. The remainder of the shaft to the top was placed via the free fall method. Data collection for TIP was initiated immediately after placement and was completed approximately 53 hours later when the peak temperature was achieved.

Table 2. Project B Shaft Details

Planned Shaft Diameter	Reinforcing Cage Diameter	Observed Shaft Length	Theoretical Concrete Volume	Placed Concrete Volume
2.74 m (9.0 ft)	2.54 m (8 ft. 4 in)	11.3 m (37 ft)	72.6 m^3 (95 cy^3)	74.6 m^3 (97.5 cy^3)

The thermal results for Test Shaft 2 are presented in Figures 6 and 7. Figure 6 presents the measured temperatures vs. depth on the left and estimated radius vs. depth on the right plot. The temperature roll-offs at the top and bottom should be ignored.

A 3-D interpretation for the shaft is presented in Figure 7. The reinforcing cage is displayed as a 2-D color spectrum with an overlay of projected shaft exterior surface to the left of these figures. The spectrum identifies the average concrete cover at each plotted depth location based on the temperature at each node.

The average calculated radius shown on the right of Figure 6 is generally consistent and above the reported drill diameter, with the exception of the lower 2.4 m (8 ft) of the shaft. The reinforcing cage appears relatively centered throughout the length of the shaft.

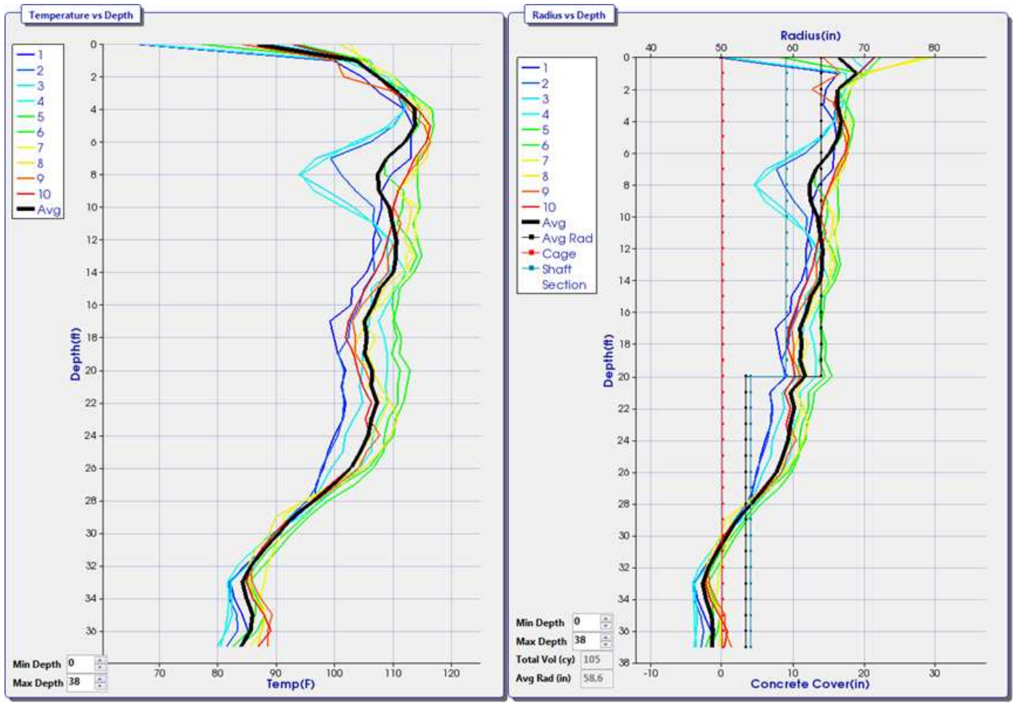

Figure 6. Project B Shaft: Measured Temperature versus Depth (left) and Estimated Radius versus Depth (right)

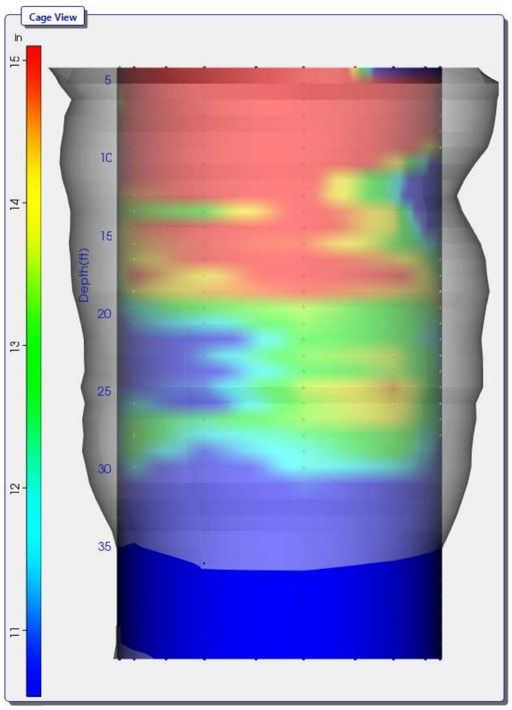

Figure 7. Project B Shaft: 3-D Interpretation

From the top of shaft to a depth of 8.1 m (26.5 ft), corresponding to the cased region, the average computed radius is consistent with the reported 1.5 m (5 ft) radius. This consistency indicates there is no reduction in radius in this region. There does not appear to be soil inside the casing in this region as reported during construction in (lower 2.0 m (6.5 ft) of cased section).

The computed shaft radius from a depth of approximately 1.8 to 3.0 m is below the nominal 1.5 m radius for the cased region and also below the design 1.37 m radius. This reduction in radius is located on the northeast face of the shaft where wires 1, 2, and 3 are located. The decline in effective radius in this permanently cased region of the shaft could indicate lower quality concrete.

Thermal results indicate the average radius is below the design 1.37 m (4.5 ft) radius from a depth of 8.5 m (29 ft) to the base of the shaft. This reduction is indicated by a decrease in temperatures recorded by all wires. This indicates that there is no concrete cover at 9.1 m (30 ft) and below.

As expected, a roll-off in temperatures is observed near the transition of the cased section (1.5 m radius) to the rock socket below (1.37 m radius). Typically this roll-off should be a slight transition; the temperatures should stabilize and trend towards vertical within the rock socket. Instead, the roll-off observed on Project B is significant and temperatures decrease linearly from 7.9 m to 10.1 m. This may be an indication of contaminated or insufficient quality concrete or of an inclusion of material in this region. Based on the reported installation procedures, it is possible that any soil that remained on the inner casing edge sloughed to the base of the shaft during installation. Further investigations were recommended for the Project B shaft, however it was determined that the observed effective radius reductions did not compromise the shaft, and further investigations were not conducted.

CONCLUSIONS

In general, QC is essential during construction of deep foundations, and especially for concrete piers that support dead-end electrical transmission structures. Even when QC is judiciously executed, construction may still result in defects. Furthermore, for foundations cast underwater, it is impossible to observe what occurs during installation. Verification of foundation integrity by non-destructive methods becomes indispensable. Although pulse echo testing, cross-hole sonic logging, and gamma gamma logging all have positive aspects, none of these testing methods alone is convenient and thorough in its investigation. All have the potential to leave unscanned ‘’blind zones” within the foundation structure.

Thermal Integrity Profiling is presented as a NDE solution with the potential to scan the entirety of a drilled shaft, both vertically and horizontally. Most importantly, it assesses the concrete cover, which none of the other methods can measure. When performed with Thermal Wire cables, it also avoids the difficulties of access tube installation commonly encountered in transmission tower foundations. TIP is also attractive because it is performed shortly after casting, sooner than other testing procedures allowing foundation approval (or corrective measures) to take place sooner.

The discovery that an installed foundation is defective becomes less devastating when project teams considered this possibility early in the project. Defects near the surface may be repairable, while significant defects at greater depths could require replacement. However, defects below a certain depth may not be critical for single pole foundations. The stresses in a foundation are not constant, with the maximum moment occurring at some distance below the ground and diminishing to zero at the bottom. Having this information determined during design will expedite decisions that would need to be made later should an engineering decision regarding a discovered defect be necessary.

Just as a good QC/QA program and documentation during construction is necessary to obtain a quality product, project teams should also plan ahead to have remedial options available should it be necessary. Lastly, the knowledge gained from integrity testing can be used to improve work practices to ultimately obtain a better, more consistent product.

REFERENCES

American Society of Testing and Materials (ASTM) (2014). *ASTM D7949-14*, *Standard Test Methods for Thermal Integrity Profiling of Concrete Deep Foundations*, West Conshohocken, PA

Mullins, A. G. (2010). "Thermal Integrity Profiling of Drilled Shafts," *DFI Journal,* Deep Foundations Institute, Vol. 4, No.2*,* 54-64

Mullins, A. G. and Ashmawy, A. (2005). *Factors Affecting Anomaly Formation in Drilled Shafts, Final Report to Florida Department of Transportation*. University of South Florida, Tampa, FL

Mullins, A. G., Kranc, S. (2007). *Thermal Integrity Testing of Drilled Shafts. Final Report to Florida Department of Transportation, FDOT Project BD544-20,* University of South Florida, Tampa, FL.

Piscsalko, G., and Cotton, D. (2011). "Non-Destructive Testing Methods for Drilled Shaft and ACIP Piles." *Proceedings from Deep Foundations Institute 36th Annual Conference on Deep Foundations*; Boston, MA, 252-532.

Piscsalko, G., Likins, G. E. and White, B. (2013). "Non-Destructive Testing of Drilled Shafts – Current Practice and New Method." *Proceedings from the International Bridge Conference:* Pittsburg, PA. (CD-ROM)

Rausche, F., April 2004. Non-Destructive Evaluation Of Deep Foundations. *Proceedings of the Fifth International Conference on Case Histories in Geotechnical Engineering*: New York, NY. (CD-ROM)