THERMAL INTEGRITY PROFILING: A RECENT TECHNOLOGICAL ADVANCEMENT IN INTEGRITY EVALUATION OF CONCRETE PILES.

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Abstract: *Cast-In-Situ concrete piles are susceptible to the creation of structural defects and imperfections that jeopardize pile's structural integrity and therefore, adversely affect pile's geotechnical capacity. By definition a deep foundation element is buried into the ground, which makes direct visual inspection of the quality of the finished product impossible. That makes integrity testing an important component of a complete quality management program. Several methods are used worldwide for the detection of possible defects in cast-in-situ concrete piles, collectively referred to as non-destructive testing methods (NDT methods). NDT methods are based on the interpretation of electronic signals collected as a result of a response to low strain or low energy excitations. The most common techniques worldwide include Cross-Hole Sonic Logging and Low Strain Integrity Testing (or Pulse Echo Test). A recent technological development, the so-called Thermal Integrity Profiling (TIP), is a very promising method for the integrity evaluation of concrete cast-in-place deep foundation elements. TIP is based on temperature measurements as a function of depth during the curing of a concrete shaft and presents several advantages over current state-of-practice NDT methods. More specifically (and unlike some of currently used NDT methods), it evaluates the entire cross sectional area of the shaft (inside and outside the reinforcing cage), does not present length-to-diameter limitations (applicable to all sizes shafts), is conducted even only few hours after the casting of the shaft -addressing accelerated construction objectives-, and presents easy and quick data collection and data interpretation. Moreover, TIP provides additional information (compared to the current NDT methods) i.e. addresses cage alignment irregularities and therefore inadequate concrete cover issues. Three case studies are presented herein (a drilled test shaft in California, a drilled test shaft in Ohio, and two full displacement bored piles in Bolivia) that demonstrate the value of TIP testing results in generating the shaft shape and identifying areas of concern (defects, soft bottoms, cage misalignments and concrete cover issues).*

1. Introduction

Cast-in-situ concrete deep foundations are widely used around the world. Types of cast-in-situ elements include bored piles, auger-cast-in-place piles, displacement continuous flight auger piles, drilled shafts, drilled caissons etc. (different names apply in different geographic areas), and will be referred to in this paper as piles or shafts. Challenging construction methods such as drilling and casting under slurry, improper construction techniques, poor concrete/grout quality or concreting techniques, unfavorable soil conditions etc. all can contribute to generating structural defects within cast-in-situ deep foundation elements. Although partial visual inspection during construction is sometimes possible (e.g. inspection of the borehole at the end of drilling in the case of dry method) visual quality assessment of the finished product is not possible. The formation of defects in drilled shafts and other cast-in-situ concrete piles, parameters affecting their development, and their effect in pile performance have been extensively discussed by many researchers and practitioners (e.g. O'Neill and Sarhan, 2004; Mullins and Ashmawy, 2005 etc.).

Structural defects, depending on their size and location, can adversely affect the load carrying capacity of the pile. It is therefore of utmost importance to implement some type of quality assurance plan to detect potential defects and take corrective measures if needed. This is particularly important when there is minimal or no redundancy in the pile design, e.g. in the case of large diameter drilled shafts designed to carry loads as single piers. Integrity testing is usually performed at a minimum on load test shafts at the beginning of construction, periodically or randomly during construction, when defects are suspected, when construction techniques change from those on load test shafts and when no redundant foundation units are used.

Two of the most common NDT methods used worldwide for that purpose are the Crosshole Sonic Logging and the Low Strain Integrity Testing or Pulse Echo Test (Rausche, 2004). A description of the two methods is given in the following sections.

A new and emerging NDT method for the integrity evaluation of cast-in-situ concrete deep foundations is Thermal Integrity Profiling (TIP). Elevated temperatures are generated during the hydration/curing phase of a concrete shaft. The TIP method uses this heat generation information, and its dissipation to the surrounding soil, to search for defects within the shaft. The main principle of the method is that a pile with a uniform cross section will produce uniform temperature profiles with depth, whereas the presence of defects will disrupt the temperature signatures. A more detailed description of this quickly emerging method, which presents many advantages over the current state-of-practice methods in integrity testing, is given in the following sections along with illustrative examples.

2. Cross-Hole Sonic Logging

One of the most commonly used NDT testing methods for the integrity evaluation of deep foundations is the Cross-hole Sonic Logging (CSL). The test configuration requires pre-installed access PVC or steel tubes attached to the reinforcement cage prior to concrete casting. Typically one tube per 300 mm of diameter with a minimum of three tubes (preferably four) are cast in the pile. The CSL principle is to measure the travel time and signal strength of ultrasonic waves travelled between two probes through concrete. The test equipment and set up used are shown in **Figure 1**.

Figure 1: CSL Testing equipment (left), a GRL engineer performing CSL testing (right)

The two probes (one transmitter and one receiver) are inserted into parallel access tubes filled with water and lowered down the pile. Both probes are pulled slowly up the pile (**Figure 1, right**) while the transmitter emits ultrasonic waves that travel through the concrete and are received by the receiver probe. Measurements of First Arrival Time (FAT) and signal strength ("energy") are taken during the pulling of the probes. Once the probes reach the top of the tubes they are moved to other access tubes within the same shaft, until all possible path combinations have been tested. Cross-hole Sonic Logging is performed in the United States in accordance with ASTM D6760.

The first arrival time and signal strength of the traveling ultrasonic waves depend on the distance between the tubes and the quality of the concrete. In uniform good quality concrete shafts and equidistant tubes, consistent arrival times and signal strength is recorded with reasonable wave speeds. Any defects within the shaft (e.g. voids, inclusions, poor quality concrete, honeycombing etc.) will delay the signal's arrival time and reduce the signal strength (amplitude). Wave transmittal is affected only by defects or lower quality concrete generally along the path between the tubes being tested, i.e. defects outside this path cannot be detected. Therefore, the concrete quality and integrity outside the reinforcing cage cannot be evaluated since the test tubes are attached to the reinforcing cage**.**

Figure 2 shows a typical CSL output consisting of a water fall diagram (right half) and FAT and energy curves (left half) with depth. In this particular example a clear defect (loss of signal) is observed at about 90 ft (27m) below pile top by a great delay in the FAT with a great drop in the energy of the transmitted signal. The loss of signal is also clearly observed by the white band in the water fall diagram at this elevation.

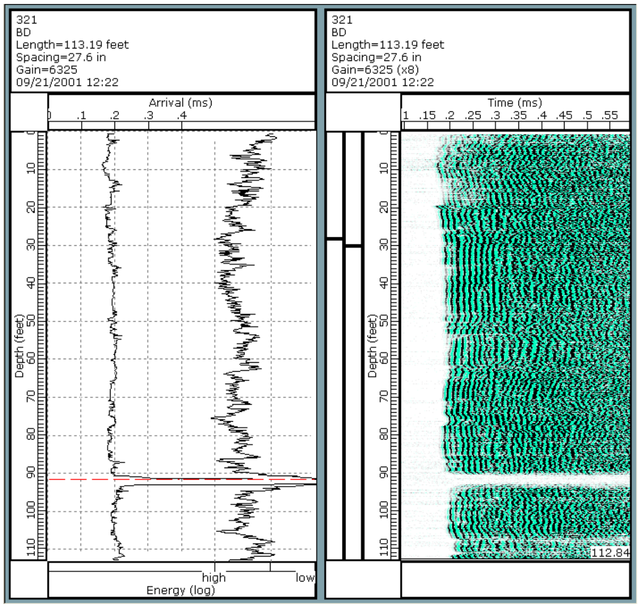

Figure 2: CSL output depicting a defect at around 90 ft below pile top.

Using a mathematical tomography approach, CSL records can also be displayed in the form of two- and three-dimensional images. An example is shown in **Figure 3**(does not represent the analysis in **Figure 2**).

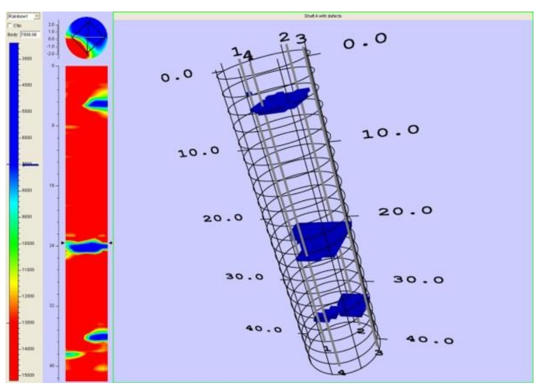

Figure 3: Tomography display of CSL records showing defects

CSL is currently one of the two most commonly used integrity test methods for deep foundations. It doesn't present any limitations as to the length of piles to be tested or surrounding soil types. It does, however, require pre-planning (installation of access tubes).

3. Low Strain Integrity Testing

Low Strain Integrity Testing or Pulse Echo Test is commonly used for integrity evaluation of deep foundation elements. In the United States this test is performed in accordance with ASTM D5882. It is a quick, easy, and inexpensive test. Unlike CSL test described above, low strain integrity testing doesn’t require pre-planning (pre-installed access tubes) in order to be performed. The test configuration consists of i) a hand held hammer (to apply a light tap to the pile top); ii) an accelerometer attached at the pile top to measure the stress wave induced by the hammer; and iii) a processing unit, which displays and stores the received signals. **Figure 4** shows the performance of a low strain integrity test using a small and convenient processing unit attached to the wrist of the engineer.

Figure 4: Low strain integrity test equipment and configuration (PIT-X Unit)

Low Strain Integrity Testing generates a low strain impact at the pile top. The associated small displacements generated from the traveling wave are gradually reduced by the surrounding soil. Therefore, for the signals from the impact to return to the pile top, a pile length-to-diameter ratio of about 45 or less is required for the test. In very competent soils that ratio is lower i.e. about 20. **Figure 5** shows the velocity vs. time records of two piles tested with PIT. The first pile shows no defect while the second one shows a clear reflection prior to the toe signal, which is an indication of an impedance reduction. Low strain integrity test data are difficult to interpret below the first major bulge or neck, leading to inconclusive data in such cases.

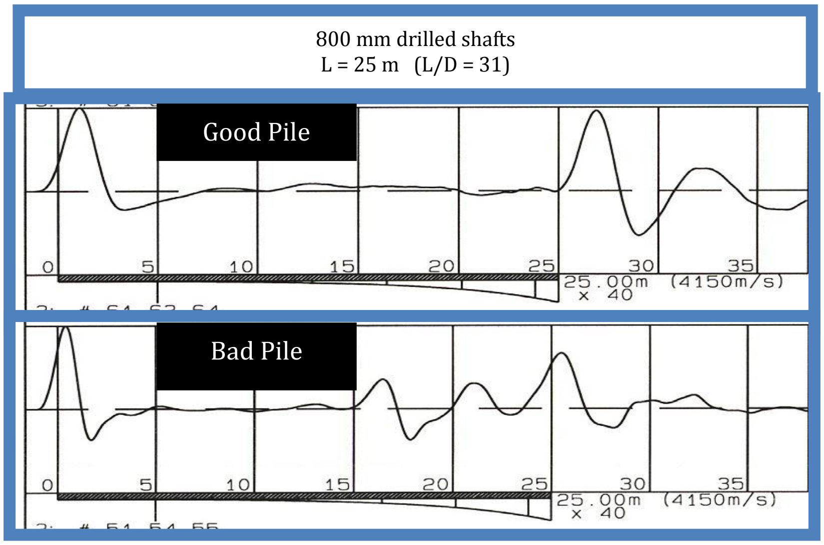

Figure 5: Low Strain Integrity Results depicting a good (top) and a bad (bottom) pile respectively.

4. Thermal Integrity Profiling

A new method for integrity testing of deep foundations is Thermal Integrity Profiling (TIP). This method is based on temperature measurements of the curing concrete soon after the concrete has been poured and when gradient temperature still exists. Elevated temperatures are generated inside a concrete shaft during concrete curing. The temperature signatures which are warmest in the shaft center and decrease toward the circumference depend on shaft diameter, concrete mix and surrounding soil conditions. For a cylindrical shaft with no defects (uniform shaft) and perfectly centered reinforcement cage, the temperature will be uniform vs. depth and around the centered cage. The presence of defects or potential eccentricity of the cage will disrupt the uniform temperature signatures.

More specifically, the presence of a soil inclusion in a certain depth would result in a sudden drop of temperature in that depth, as shown in **Figure 6,** because of the absence of heat producing cement content at that location. For relatively small diameter shafts, this defect will also be evidenced in locations further away but the temperature reduction effect will be less severe. Obviously, a bulge would have an increase in temperature due to the nearby presence of additional heat producing cement content. Misalignment of the reinforcing cage, results in measured temperature profiles (in radially opposite locations) that are shifted with respect to each other as shown in **Figure 7**. Measurement location A1 is closer to the center and thus warmer, whereas measurement location A2 is closer to the surrounding soil and hence cooler as can be seen in **Figure 7**. This gives information on adequacy of concrete cover when misalignment of reinforcement cage is present.

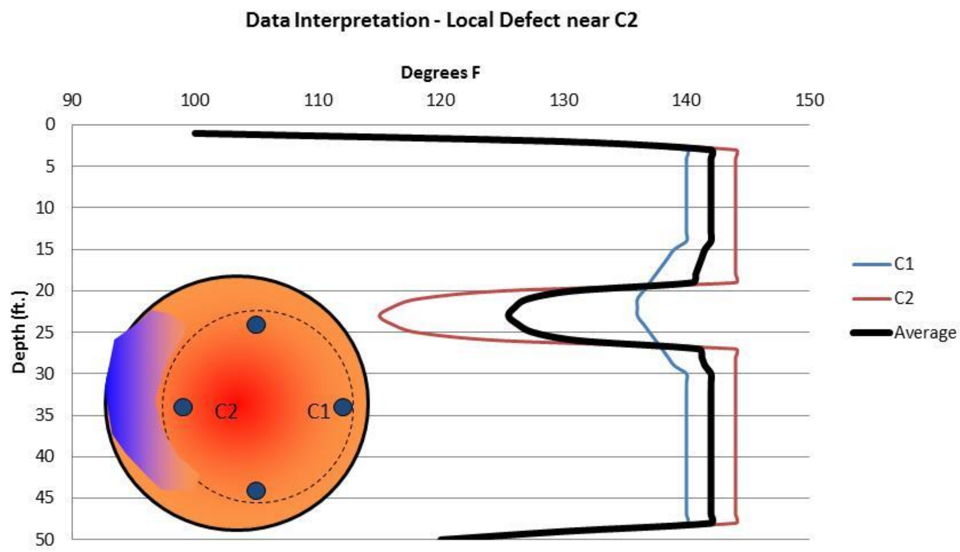

Figure 6: Temperature drop at around 20 ft due to the presence of defect.

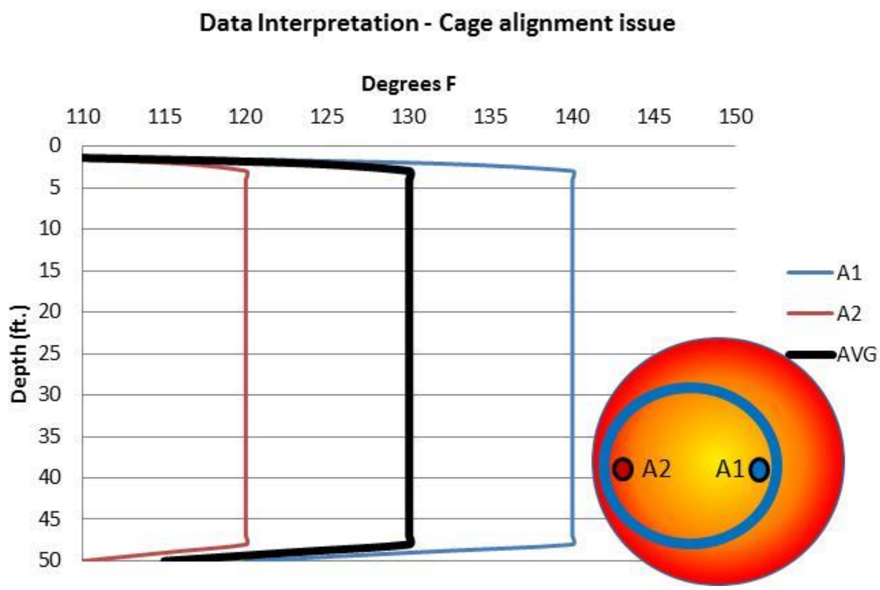

Figure 7: Temperature shift between wires A1 and A2 due to cage misalignment.

Temperature measurements can be made either with infrared probes inserted into dewatered CSL-like inspection tubes (as shown in **Figure 8**), or with Thermal Wire® brand cables attached to the reinforcing cage prior to casting the shaft (**Figure 9**) and continuous temperature monitoring can be made in preselected time intervals.

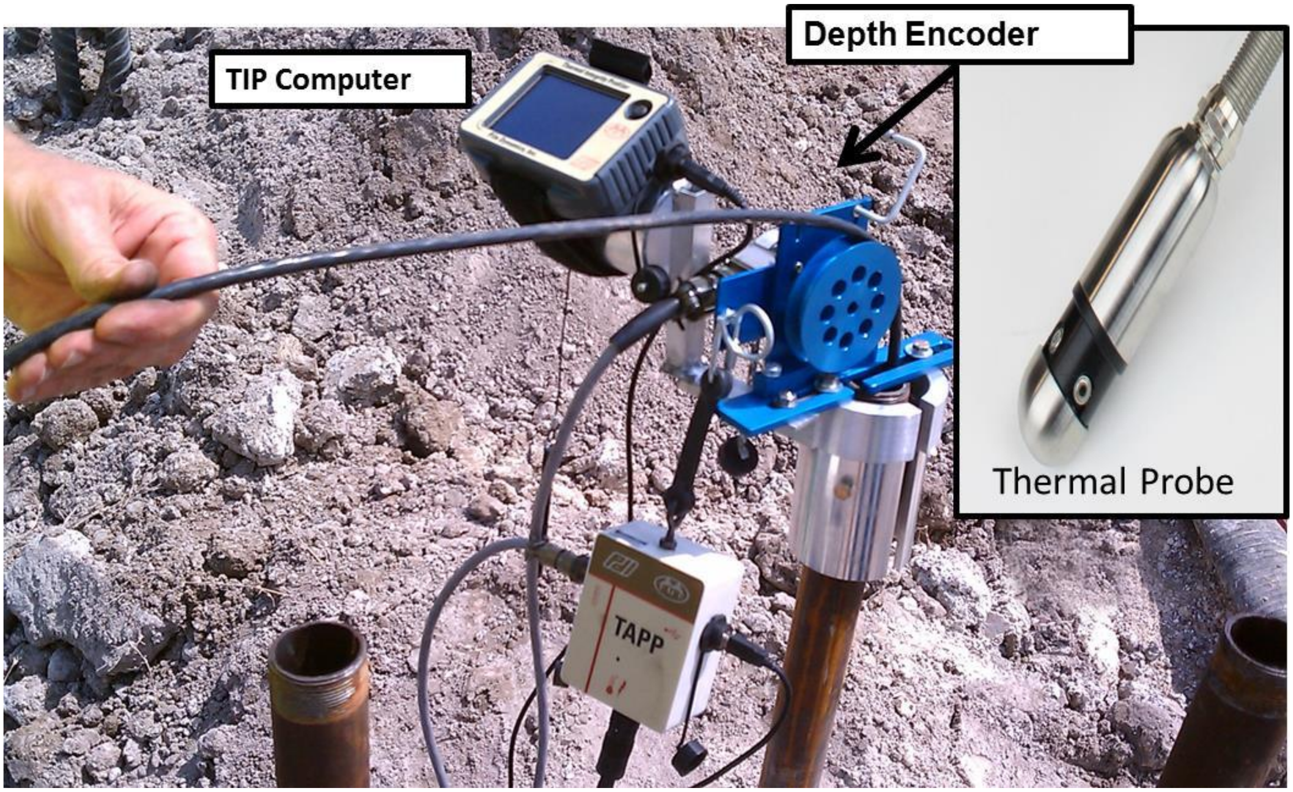

Figure 8: Thermal Integrity Profiler test configuration (probe method)

Figure 9: Thermal Wire cables installed in the cage (left), TAP data collector units connected in the cables (right)

Defects and eccentricity can be quantified based on the thermal measurements and the concrete volume information. Data interpretation is very straightforward and requires very little from the user, while a 3-D image of the pile can easily be generated from the measured temperatures and concrete volume information (**Figure 12, Figure 16, Figure 19, and Figure 21**). More information on TIP can be found in Likins and Mullins (2011), Mullins and Winters (2011), Mullins (2010), and, Mullins and Kranc (2007).

Thermal Integrity profiling presents many advantages over the current state of practice NDT methods used for integrity evaluation of concrete cast-in-situ piles.

- One of its major advantages is providing full evaluation of the cross sectional area i.e. both inside and outside the reinforcing cage.
- Extra information is provided by the thermal method compared to other NDT methods; i.e. cage misalignment and therefore inadequate concrete cover issues can be addressed. This is important because although defects may not be present in the core of the shaft, concrete cover can still be reduced beyond an acceptable limit due to cage eccentricity.
- The thermal method is not limited to any pile length-to-diameter ratios, i.e. any pile can be tested regardless its length or diameter.
- Testing is conducted within a few hours after the concrete casting, i.e. typically within the first 48 hours from casting, which is particularly important when accelerated construction is an objective.
- Data collection is very quick, especially when the wire method is used.
- Data analysis is very quick and straightforward and interpretation does not present sensitivity to the interpreter.
- The test does not seem to give false positive identifications although a comprehensive study that measures the false positive identification rate cannot be referenced yet.

5. Case Studies

Halstead Meadows Bridge - Sequoia National Park, California (Case A): The Halstead Meadow Bridge was constructed to serve as a replacement bridge in the Sequoia Park in California. This six span bridge is founded in 36-inch (914.4mm) drilled shafts with lengths ranging from about 40 ft to 60 ft (12.2m to 18.3m). Four drilled shafts were installed in each abutment and each bent of the bridge. Crosshole Sonic Logging and Thermal Integrity Profiling were required as part of the quality assurance specification of the project. One of the production drilled shafts (Shaft A) tested with both the CSL method and TIP method is shown in **Figure 10**.

Shaft A was drilled under polymer slurry with a nominal diameter of 36 inches (914.4mm) and a measured length of about 48 ft (14.6m). A full length 30-inch (762mm) diameter reinforcement cage was used along with a 30-ft (9.1m) long steel casing in the upper pile portion to assure soil stability. Installation records showed 15 cubic yards (11.5m^3) of concrete were used for Shaft A. Four thermal wires and three steel CSL access tubes were installed. **Figure 10** shows the installed thermal wires coming out of the pile top and connected to the TAP units (thermal acquisition ports) as well as the steel CSL tubes extruding from the top of the pile.

Figure 10: Test Shaft A - Halstead Meadows Bridge - Sequoia National Park, California

Thermal measurements and actual concrete volume information from concrete logs were input to the TIP Reporter software for thermal analysis to estimate the shaft radius. **Figure 11** presents the measured temperature profiles with depth from the four installed wires and their calculated average. From the analysis of thermal data, the shaft radius vs. depth and a 3-D image of the as-built shape of the shaft is calculated and presented in **Figure 12 (**cage radius of 15 inches (381mm) is also plotted as a red-dotted reference line). Based on these results, the outside shaft radius in the cased upper 30 ft (9.1m) is seen relatively uniform (as expected due to the casing). Slight variations in calculated radius are due to changes in concrete quality or soil layer properties (conductivity or temperature) rather than size variations. An exception would be the top few feet of the shaft where overflow concrete filled a void between soil and casing.

Below the cased shaft section, a bulge appears starting at approximately 32 ft (9.8m) beneath the shaft top, reaching a peak radius of 25 inches (635mm), (averaged over all four wires). From the thermal output, a soft toe condition is also evidenced at the bottom of the pile. More specifically, below about 40 ft (12.2m) the as-built radius falls below the design radius (green dashed line) of 18 inches (457mm). **Figure 13** shows the CSL results performed on the same pile, which clearly depict the encountered soft toe. In the pile section where CSL records indicate the soft toe (at about 46 ft (14m) and below), TIP results indicate a reduced pile radius with an average value of about 13 inches (330mm) in this section. As can be seen in **Figure 12** and **Figure 13**, CSL depicts the radius reduction to occur from about 46 ft (14m) to the bottom of the shaft, whereas TIP shows the problematic area from about 40 ft (12.2m) all the way to bottom of the shaft. This difference is attributed to the fact that the CSL test cannot detect defects outside the reinforcing cage. At about 45-46ft (13.7m to 14m), the pile radius reduction finally starts affecting the area inside the cage (shaft radius becomes less than cage radius as can be seen from TIP results, **Figure 12**) where the problem can be seen by CSL. Obviously, TIP interpretations supersede CSL interpretations as it captures the radius reduction not only in the section below 46 ft (14m) but also in the section from 40ft to 46 ft (12.2m to 14m) where the shaft radius becomes less than the design radius.

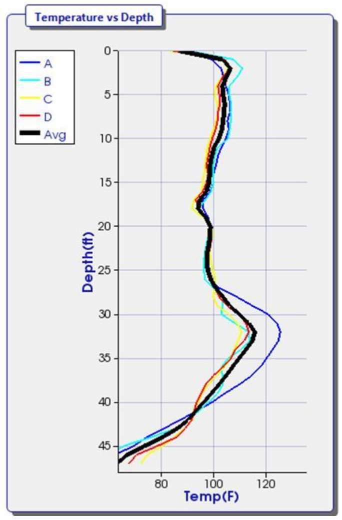

Figure 11: Shafts A – Measured Temperatures (4 wires and average).

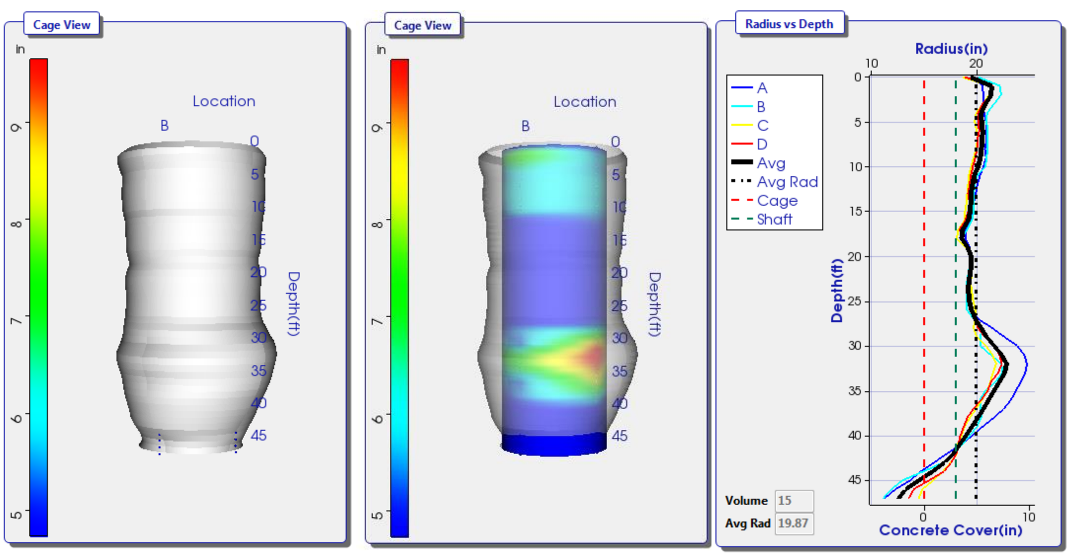

Figure 12: Shafts A – Radius vs. depth estimation and 3-D Imaging.

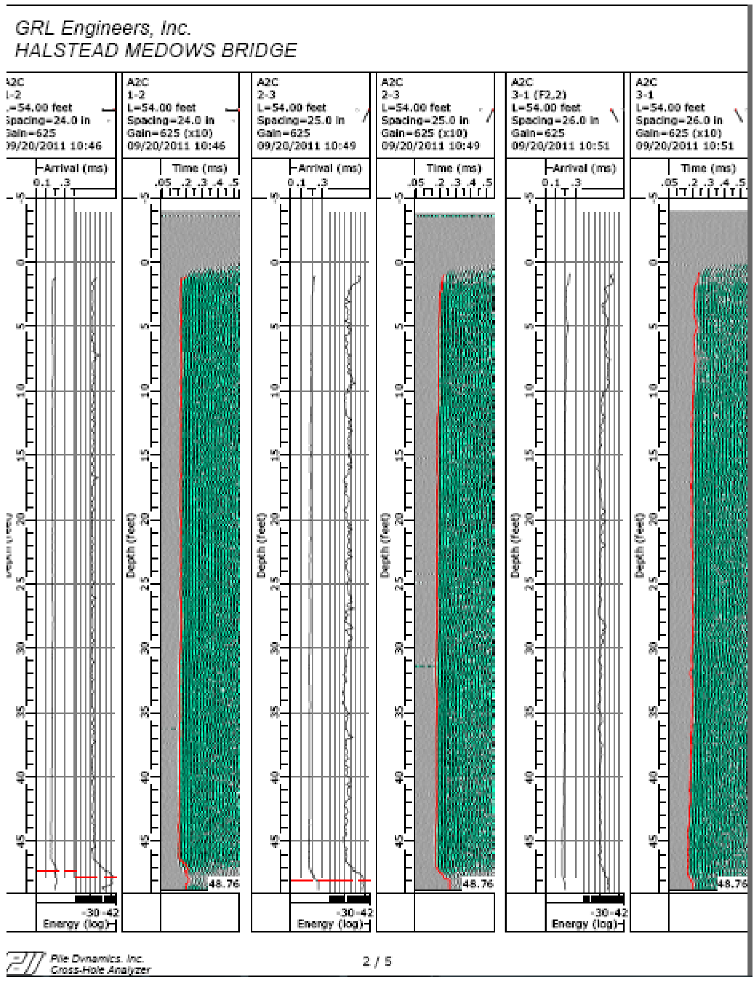

Figure 13: Shafts A – CSL Test Results.

<u>Inner Belt Demonstration Shaft – Cleveland, Ohio (Case B):</u> Two bridges are to be constructed to replace the aging I-90 viaduct in downtown Cleveland, Ohio. The first Inner Belt Bridge, already under construction, will be completed by late 2013. A demonstration shaft, heavily instrumented for integrity and capacity evaluations, was constructed and tested on-site. The test shaft was a 66-inch (1.7m) diameter, 179.5 ft (54.7m) long shaft with a 54-inch (1.4m) diameter full length reinforcement cage. An 84-inch (2.1m) diameter temporary steel casing was in place for the upper 28 feet (8.5m). Actual concrete volume was 191 cubic yards (146 m^3), which is 121% of the theoretical concrete volume (158 cubic yards (120.8m^3)). The rebar cage was built with 20 vertical bars in two sections, with a 10-foot (3.0m) overlap for splicing. The shaft was heavily instrumented including eight thermal wire cables, an Osterberg Cell installed near the shaft toe, six PVC tubes installed inside the cage for CSL testing, and four PVC tubes installed outside the cage for Gamma-Gamma testing (GGL). All tubes were terminated at the top of the Osterberg Cell. The

Thermal wire cables were delivered in 100-foot (30.5m) sections, and spliced with a quick connect waterproof connector at the splice location. Six of the wires extended from the top of the shaft to the top of the Osterberg Cell. The remaining two wires extended past the cell to the bottom of the rebar cage. A picture of the TAP data collection units at the top part of the instrumented cage installed in the shaft is shown in **Figure 14**.

Figure 14: Innerbelt Test Shaft, Cleveland, Ohio

Figure 15 presents the measured temperatures and their calculated average. **Figure 16** presents the calculated shaft radius and a 3-D image of the shaft based on interpretation of thermal data and actual concrete volumes.

It is apparent that the radius of the top 28 ft (8.5m) (cased section) averages about 40 inches (1.0m), roughly corresponding to the temporarily casing diameter. Moreover, it is evident from **Figure 15** that locations near wires 6 and 8 (as well as 1 and 5 to a lesser extent) are warmer than the average and thus the cage at that quadrant is closer to the shaft center. Temperatures measured near wires 2 and 3 are cooler than average and thus the cage is closer to the perimeter of the shaft in that quadrant. However, and despite the cage eccentricity, the concrete cover in this section exceeds the nominal 6 inch (152mm) value, and in fact is larger than 9 inches (229mm). The radius below 28 ft (8.5m) is practically constant until about 127 feet (38.7m), with a generally well-centered cage (as is evident by the overlapping of temperature measurements of the various wires) and typical cover of about 8 inches (0.20m). Between the depths of 127 ft to 134 ft (38.7m to 40.8m) a small bulge is observed based on thermal analysis output. This shaft radius increase can be explained by the interruption of concreting activities after about 50 ft (15.2m) of shaft had been poured, and the extra pumping through the tremie during the waiting period.

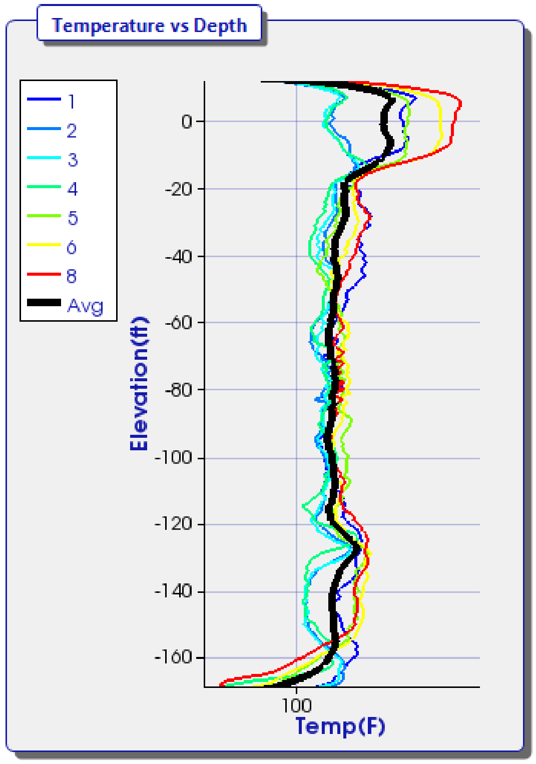

Figure 15: Innerbelt Test Shaft – Measured Temperatures.

From 134 ft (40.8m) to about 160 ft (48.8m) depth, the shaft returns to the typical radius observed above the time delayed, tremie-induced bulge (centered at 130 ft (39.6m)). The cover during this depth exceeds 7 inches (178mm) and averages 9 inches (229mm). Below the depth of 160 ft (48.8m), a temperature drop is observed associated with the presence of the Osterberg cell.

Samples of CSL testing as well as GGL results are presented in **Figure 17**. CSL results did not show any decrease in First Arrival Time or energy, which would be an indication of a defect. GGL results also did not show defects. A localized density drop was observed at a penetration of 118 ft (36.0m) in one of the access tubes installed outside the cage. At that same elevation, nearby measurements evidenced a minor decrease in temperature. As evidenced in the radii calculations by TIP, this decrease does not substantially affect the concrete cover at this location and elevation. CSL and GGL were not able to detect the presence of the O-cell, as expected, since the O-cell is located below the bottom of the access tubes. Moreover, CSL and GGL cannot estimate the as-built shape of the shaft like TIP does. No defects were found by any of the three methods: CSL, GGL and TIP.

The top 15 ft (4.6m) of the shaft was later excavated. **Figure 18** shows the bulge as well as the cage eccentricity located near the top, so clearly predicted by Thermal Integrity Profiling.

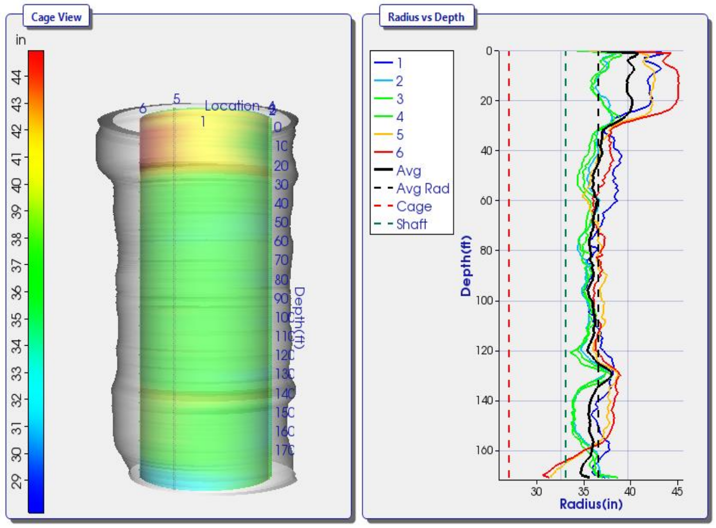

Figure 16: Innerbelt Test Shaft – Shaft shape as derived by TIP including location of the reinforcement cage (left), radius vs. depth profiles as calculated by TIP (right).

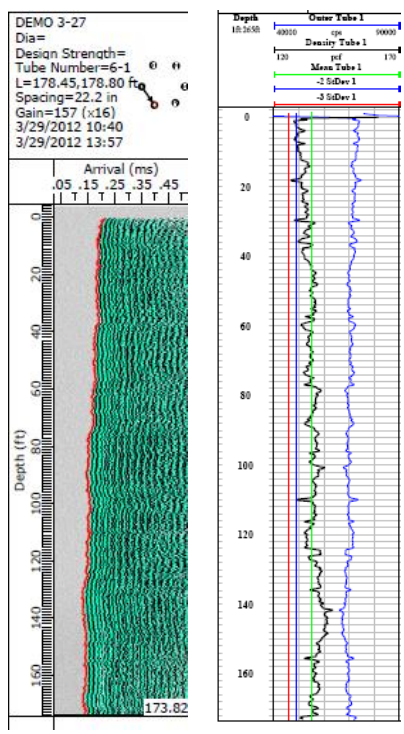

Figure 17: Innerbelt Test Shaft – CSL and GGL Sample Results.

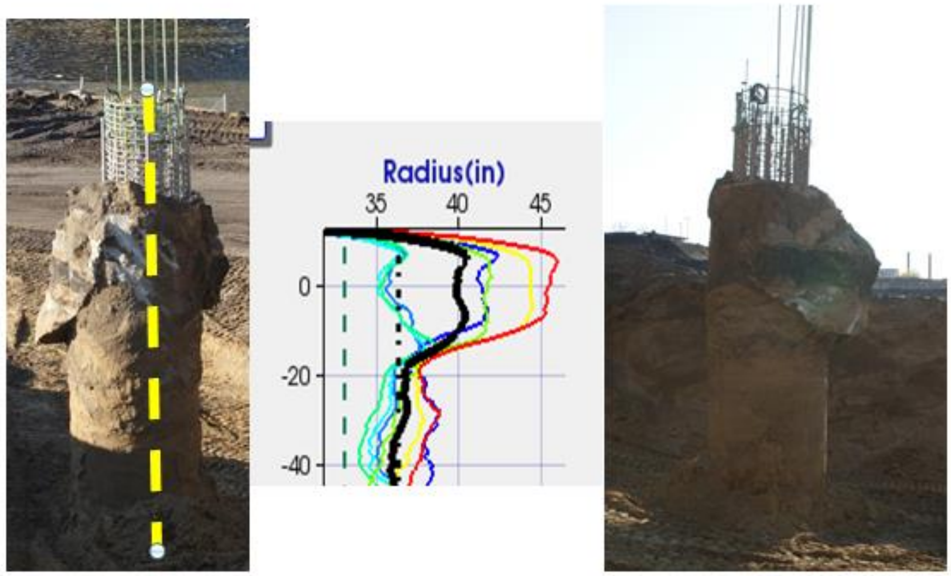

Figure 18: Innerbelt Test Shaft – Pictures of Top Excavation

<u>**Bolivia Prediction Event (Case C):**</u> A capacity prediction event organized in conjunction with the 1st International Conference on Deep Foundations in Santa Cruz, Bolivia includes four test shafts that will be statically and dynamically load tested. All four shafts are instrumented with thermal wire cables for integrity evaluation prior to load testing. The test shafts are small diameter (36 cm to 40 cm nominal diameter) bored piles of various lengths ranging from 10.8 m to 17.5 m. Test Shaft TP2 is a full displacement bored pile with a diameter of 36 cm and a length of 11.6 m. Two thermal wires were installed in its full length reinforcing cage of 26 cm diameter. The time selected for the analysis is about 14 hours after concrete pouring. Based on thermal data interpretation and total concrete volume information, the as-built shaft shape is calculated as shown in **Figure 19**. The radius vs. depth profile as calculated by thermal data is also shown in the same figure, with the design shaft radius and design cage location plotted for reference (green dotted line and red dotted line, respectively). Concreting information (concrete pressures, volumes and concreting time) are shown in **Figure 20**. **Figure 19** depicts a very well-constructed shaft. Test shaft TP2 is practically uniform with depth, with an average shaft radius of 22 cm (4 cm higher than the design radius of 18cm) with a small bulge between about 3m to 4m. The small bulge between about 3m to 4m depth can be explained by the sloughing of the loose sands at the water table elevation.

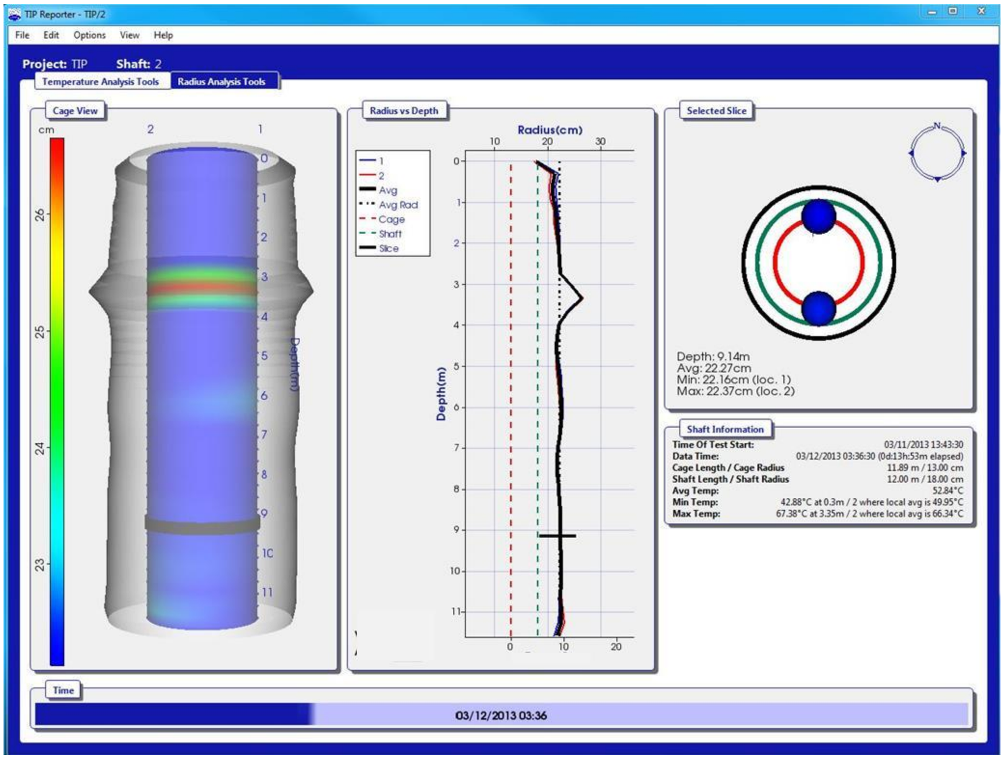

Figure 19: TP2, Bolivia – Radius vs. depth estimation and 3-D Imaging.

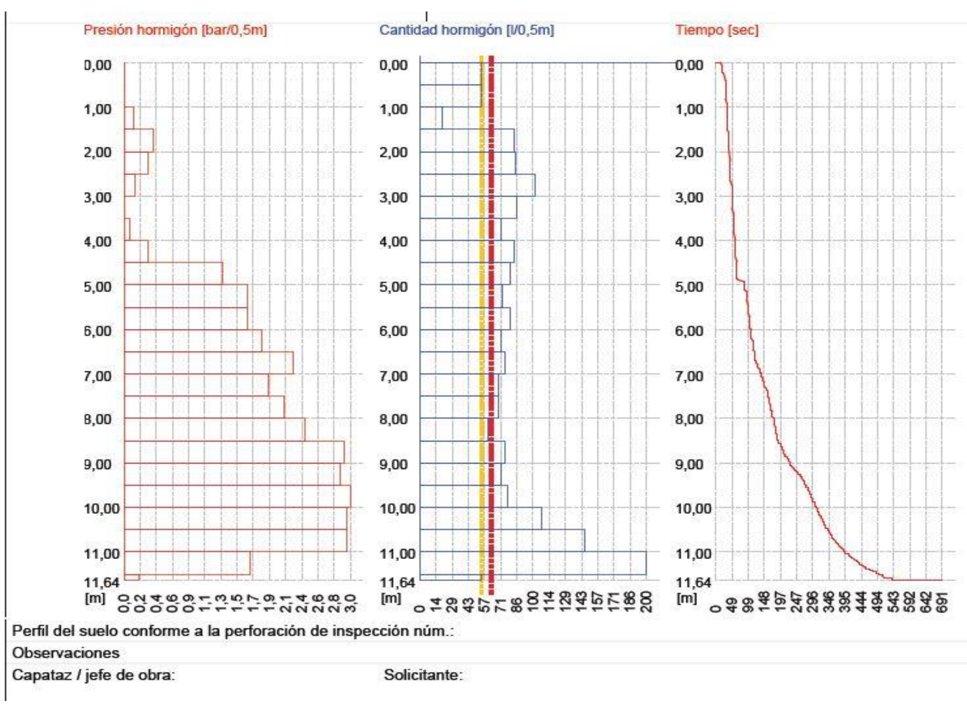

Figure 20: TP2- Bolivia, Concrete pressure (left), concrete volume (middle), concreting time (right)

A looser sand layer encountered at that level (based on borehole and SPT information) together with the water level encountered at the same level (about 3 m), probably resulted in a slight over-excavation of the soil as the auger entered that layer. This is in agreement with the concrete pressure and volume information reported for this pile. As can be seen in **Figure 20** concrete volumes are higher around 3 m depth, whereas concrete pressures are very low in that region.

Concrete pressures substantially increase below that region although concrete volumes somewhat decrease. A concrete cover of 9 cm (higher than the design of 5 cm) is demonstrated for the full length of the shaft (except from the small bulge area, where cover is slightly higher) with an almost perfectly centered reinforcement cage.

Similar conclusion can be drawn for test shaft TP3, constructed adjacent to TP2. TP3 is similar in construction to TP2 with the only difference being a length of 10.8m and an expandable body being installed at the bottom of the shaft. Only the top 6m were instrumented with thermal wires and therefore only that part of the shaft is analyzed and illustrated in **Figure 21**. As can be seen the shape of the TP3 is very similar to the TP2 for the length analyzed.

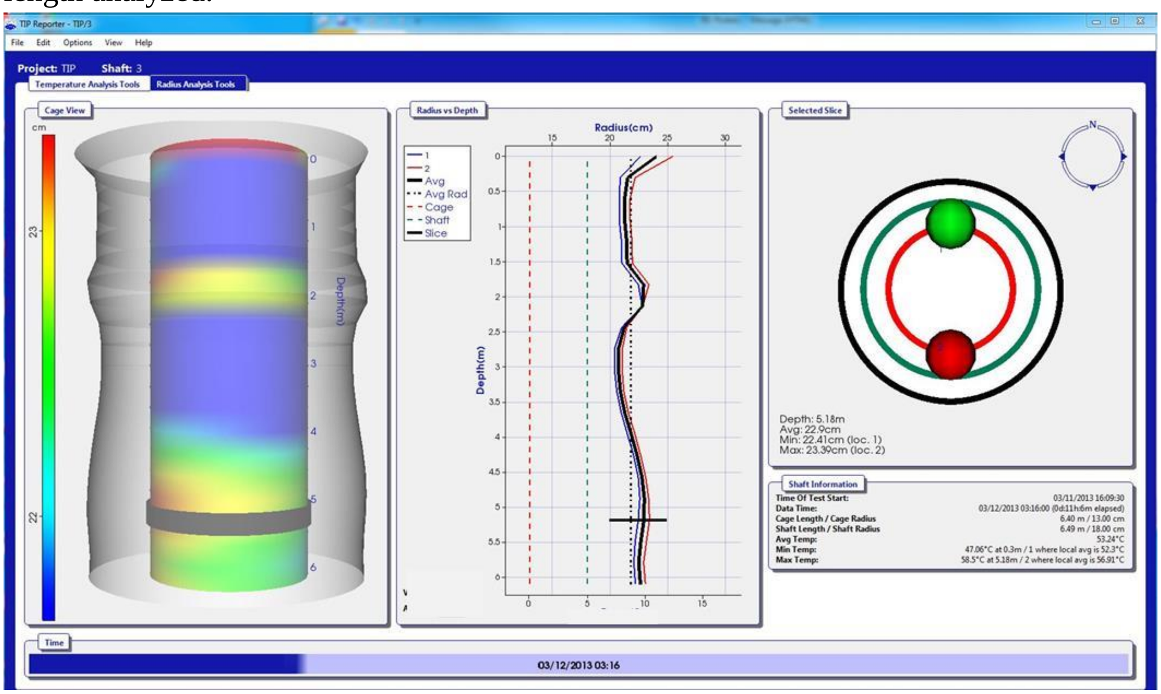

Figure 21: TP3, Bolivia – Radius vs. depth estimation and 3-D Imaging.

6. Summary/Conclusions

Thermal Integrity Profiling is a very promising method for the integrity testing of concrete deep foundations. It is based on measurements of temperatures that are generated inside the concrete shaft during the curing/hydration process. The high internal temperatures induced inside the shaft reach a peak value typically within the first 48 hours of casting. Heat generation signatures and dissipation to the surrounding soil depend on concrete mix, shaft diameter and slightly on the surrounding soil environment. The presence of defects and cage misalignment alter the heat signatures and, therefore, thermal data can be analyzed to quantify these effects and evaluate the integrity and general shape of the shaft. If measurements for analysis are taken with infrared probes, they should be taken while temperature gradients still exist within the shaft. If thermal wire cables are used, measurements are taken continuously in pre-specified time intervals and the most appropriate time for analysis (generally the peak temperature) is selected for analysis. TIP is based on a sound theoretical basis and eliminates many of the limitations associated with the current state of practice methods, while it provides additional information than these methods. More specifically, TIP scans the cross sectional area of the shaft inside and outside of the reinforcing cage for defects; it evaluates reinforcement cage alignment and therefore concrete cover issues; it requires less waiting time between concrete pouring and integrity testing as it is capable of inferring results very soon after the concrete casting (the contractor/engineer knows the condition of the shaft soon after construction); collection and interpretation of data is very easy and fast and doesn't require specialized knowledge from the user; finally, it does not present length-to-diameter limitations and therefore is applicable to all concrete shafts. TIP output includes, among the other information, a 3-D image of the as-built shape of the shaft (automatically generated by the use of thermal data and concrete volume information). TIP output illustrates shaft radius variation with depth, bulges, defects, cage misalignment, concrete cover, soft bottoms etc. TIP has already been applied to numerous case studies all around US and abroad (three case studies are presented in this paper). The test predicts the shaft shape and detects areas of concern.

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