Case Histories Utilizing Thermal Integrity Profiling for Foundation Quality Assurance

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ABSTRACT
Advances in Quality Assurance and Quality Control (QA/QC) of foundation elements, including drilled shafts and Augered-Cast-In-Place piles, have been achieved using Thermal Integrity Profiling (TIP). This Non-destructive testing (NDT) method utilizes the heat generation of curing concrete to assess drilled shaft shape and overall quality. Temperature measurements along the length of an element are recorded during the concrete hydration process following placement. These temperature measurements along with volume information and installation details can be used to model the effective shaft radius and shape. Recent TIP projects have displayed evidence of local anomalies within the collected data. This paper presents several case histories on projects where TIP was implemented and compared with additional field verification measurements, and provides an evaluation and discussion of project outcomes.

RÉSUMÉ
Des avancées en matière d'assurance qualité et contrôle qualité (QA/QC) des puits forés et pieux forrés cimentés ont été atteintes grâce à la technique du profilage thermique (Thermal Integrity Profiling – TIP). Ce test non destructif (NDT), basé sur la mesure de dissipation thermique du béton en phase de curage, permet d'évaluer la forme, ainsi que l'integrité des pieux cimentés. Le principe repose sur des mesures de température à intervalles reguliers le long du pieu, ainsi que sur son partour; pendant la phase d'hydration du béton. Ces données de température, coroborées avec d'autres informations tels que le volume de béton et les détails d'installation, sont utilisées pour modéliser la forme et le rayon effectif du pieu. Cet article présente différents cas ou le TIP a été utilisé, et compare les résultats avec d'autres méthodes d'investigations:

1 INTRODUCTION

Drilled shafts and Augered Cast-In-Place piles are commonly utilized as deep foundation elements on projects across the world. They are popular choices due to the high axial and lateral capacities that are obtainable. However, due to the construction procedures and installation techniques required to install a drilled shaft element, the final in place product is often difficult to impossible to inspect. Improper drilling techniques, poor concrete quality, weak and saturated soils, and improper concreting techniques may all contribute to the formation of defects and anomalies within these deep foundation elements. Quality assurance is critical to ensure the placed foundation meets the intended design parameters.

When deep foundations are utilized, they often consist of concrete or grout, which is cast directly at the service location. Consequently, this type of foundation does not easily lend itself to visual inspection for structural integrity. Although several Quality Assurance / Quality Control (QA/QC) methods are available to assess structural integrity, this paper will highlight the results of Thermal Integrity Profiling (TIP). This method is performed in accordance with ASTM Standard D7949.

Thermal Integrity Profiling involves collecting temperature measurements at many locations within the freshly cast deep foundation. The basic objective is to measure the heat generated by the chemical hydration process of the cement, which is dependent primarily on the chemical composition in the concrete and the mass of the various components. (Mullins et al, 2005, 2007, and 2011). Ideally, the temperatures should be collected at the time, or just prior to, when the maximum temperatures are produced (due to the heat of hydration of the curing cement). Since this normally occurs within 8 to 48 hours, after casting, depending on the shaft diameter, the most common method of data collection is by utilizing Thermal Wire® cables that are secured to the full-length rebar cage. The Thermal Wire cables contain digital temperature sensors equally spaced (approximately every 0.3 meters). The number of Thermal Wire cables applied to the rebar cage usually depends on the nominal dimension of the concrete, with each cable typically paired with another placed on the opposite side of the cage. This paper presents several examples demonstrating the use of TIP, and information that can be obtained from the results.

2 CASE HISTORY #1

Construction of the new Ocosta Elementary School in Westport, Washington State consisted of a new building, including a gymnasium with an approximately 40-foot tall roof structure. Due to the site being located in a potential tsunami zone, the roof is to serve as a tsunami refuge (vertical evacuation) structure and the foundation is therefore designed to withstand scour and earthquake shaking forces. The structure is founded on 18 and 24-inch diameter augercast piles. The soils generally consist of loose to medium dense sand to a depth of 20-25 feet, then dense sand to 32 feet, followed by a few feet thick clay layer below that, and dense sand at deeper depths.

Select piles were chosen to be instrumented with TIP Thermal Wire cables, with two wires being placed on diametrically opposite sides of the full-length rebar cage.

Pile 37 was one of the selected piles for TIP testing. This pile was 24-inches in diameter and had a total reported length of 48 feet. The theoretical volume of this pile is 5.62 yds^3, while the actual reported volume constructed is 8.80 yds^3, and the rebar cage diameter is 18-inches.

2.1 Results

Peak temperature for Pile 37 was reached approximately 12 hours after concrete placement. The measured Temperature (degrees Fahrenheit) vs. Depth (feet) for each Thermal Wire cable, is presented in Figure 1.

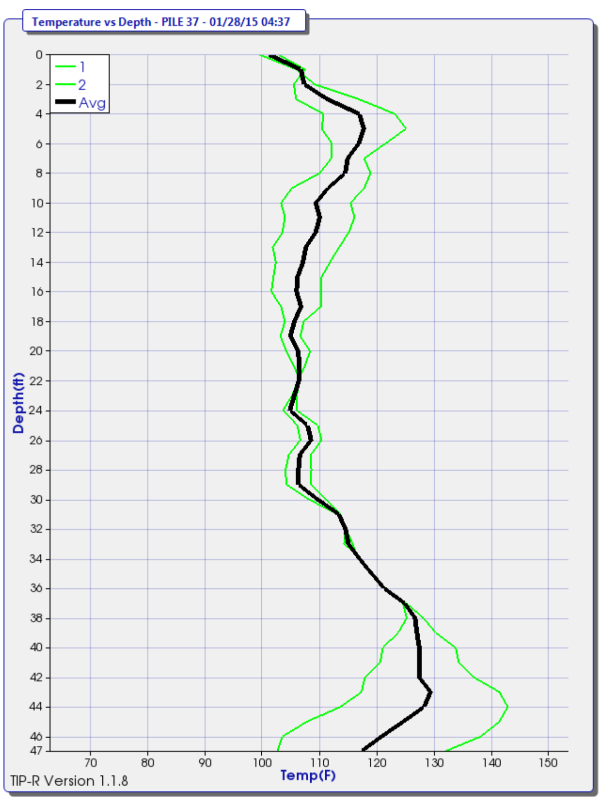

Figure 1. Pile 37 – Temperature vs. Depth Plot

Note that there is a decrease in temperature at both the top and bottom ends of the pile, as would be expected due to the top and bottom surfaces allowing for an increased amount of heat dissipation, compared to the body of the shaft. The average temperature curve along the main length of the pile would be directly relative to the pile mass at each location, assuming the composition of the concrete is homogeneous throughout. When the roll-off of temperature at the pile ends (2 diameters) is accounted for, and incorporating the known volume of the pile, the radius of the concrete can be determined as a function of depth. Figure 2 presents the Effective Average Radius vs. Depth as well as the Effective Local Radius vs. Depth.

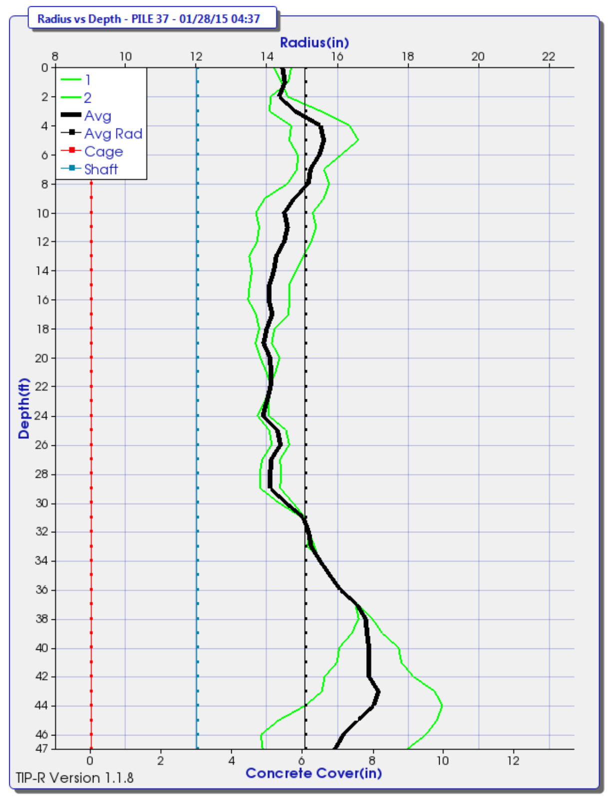

Figure 2. Pile 37 – Pile Radius vs. Depth Plot

The design radius of the cage and shaft are also indicated in Figure 2 for comparison. A significant feature in this data is the separation or variation in temperature at corresponding depths, particularly in the bottom 10-feet, and also within the top 20- feet. The observed variation in temperature for diametrically opposite wires indicates that the cage is not concentric at these locations, but rather shifted to one side, relative to the pile axis. Since the temperature will be highest at the axis of the pile, and lowest near the soil interface for any typical cross-section, the relative shift in the cage can be determined from opposing Thermal Wire cables. A location where the cables are approximately equidistant from the pile axis would be from depths of approximately 31 to 37 feet, where the temperature of both cables are similar. It has been estimated that for opposing cables, that approximately five degrees Fahrenheit variation from the average temperature equates to approximately one inch of cage shift. Following this method, the cage for Pile 37 has shifted approximately 3 inches maximum near the bottom, and between 1 and 2 inches within the top 20 feet.

3 CASE HISTORY #2

In the development of TIP testing the results are often compared against other non-destructive integrity test methods. The next case study presents data from two load test shafts located in Phoenix, Arizona for the SR202 and I-10 interchange project. This project presented a unique opportunity to compare the results of TIP testing with the results of a borehole caliper. The subsurface conditions reportedly consisted of primarily sandy clay and silt.

For the purposes of this paper the shafts are referred to as TS-1 and TS-2. Each drilled shaft was reportedly 100-feet in length and 72-inches in diameter. A full length reinforcing cage which measured 60-inches in diameter was placed in each shaft prior to placement. Prior to the placement of the cage into the excavated shaft, six Thermal Wire cables were spaced equidistantly around the perimeter of the cage and instrumented along the full length. An Osterberg Cell (O-Cell) was attached to the cage of each shaft and positioned at a depth of approximately 75-feet for TS-1 and 65-feet for TS-2. In addition to the O-Cell, each shaft was also equipped with six access tubes for Cross-Hole Sonic Logging (CSL) and also for Gamma Density Logging.

After each shaft was excavated and prior to the setting of the rebar cage and concrete, a borehole caliper tool was lowered down each shaft. The mechanical borehole caliper is an inspection device that measures the diameter and shape of a borehole prior to concrete placement. Once lowered to the base of the excavated shaft, the mechanical arms make contact with the borehole wall and measure the diameter over the shaft length as the unit is raised. The mechanical caliper used for inspecting TS-1 and TS-2 is shown in Figure 3.

Figure 3. Photo of mechanical caliper

3.1 Results

Peak temperature for TS-1 was reached 40.5 hours after placement while TS-2 reached peak temperature 14.5 hours after placement. The TIP analysis for both shafts was performed at these corresponding times. After the top of shaft and bottom of shaft roll-off adjustments were applied to each shaft and the reported concrete volume was accounted for, the shaft radius as a function of depth was plotted. A side by side comparison of the thermal results and caliper results is presented in Figures 5 and 6. The left side of the Figures presents the Estimated Radius vs. Depth graph while the right side presents the Caliper Results.

Figure 4. Photo of rebar cage for TS-2

A direct comparison of the collected data supports a strong correlation between the estimated radii using TIP and the mechanical caliper. The overall shape of the borehole prior to concrete placement as measured by the caliper is very similar to the estimated radius as calculated by TIP after the placement of concrete (shown as the heavy black average line in Figures 5 and 6). The main difference between the collected data appears to be in the region of the O-Cell. However, note that the O-Cell was not present in the excavated borehole when the caliper was performed. In the TIP results, the O-Cell is evident as a slight reduction in temperature. The high volume of steel at the O-Cell location acts as a heat sink where all recorded measurements typically reduce to a similar temperature reading. Note that for TS-1, there is an increase in concrete cover (bulge) directly above the O-Cell that appears to have reduced the effect of the heat sink due to the increase in heat producing cement present within close proximity to the O-Cell.

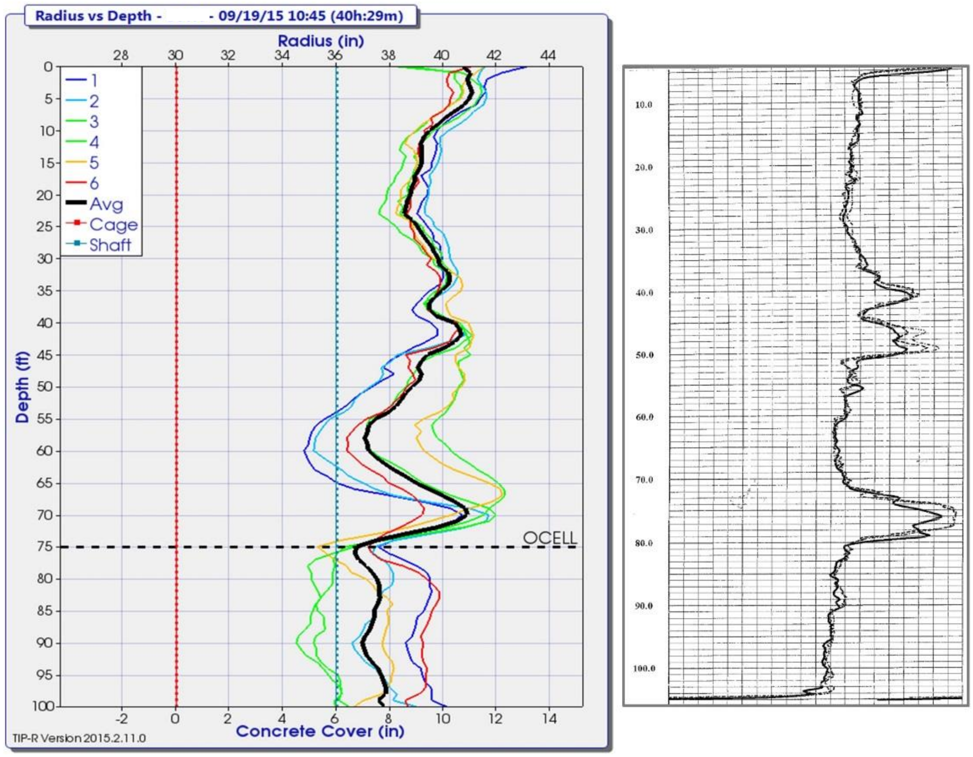

Figure 5. Comparison of Estimated Radius vs. Depth and Caliper Results: TS-1

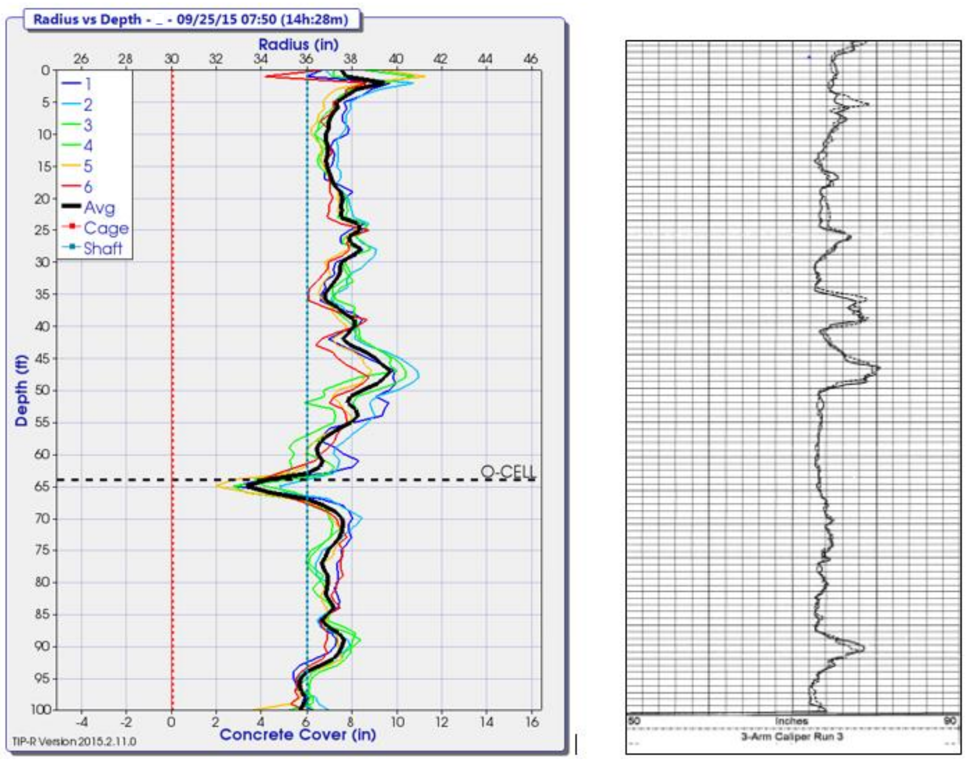

Figure 6. Comparison of Estimated Radius vs. Depth and Caliper Results: TS-2

4 CASE HISTORY #3

The final case presented is a 9.84-foot diameter drilled shaft that was constructed on the I-5 – Portland Avenue to Port of Tacoma Road – Northbound HOV Project in Tacoma, Washington. This shaft was constructed as part of a widening project on I-5, to add High Occupancy Vehicle (HOV) lanes to relieve congestion. Part of the project includes replacing a bridge over the Puyallup River. A soil boring performed near the shaft location indicated layers of silt and silty sands from the top of shaft Elevation (EL.) 2.3 to EL.-110. This was underlain by a silty gravel layer that continued to the shaft toe at EL.-125.4. As part of the quality control plan, all drilled shafts placed on this project were evaluated using Thermal Integrity Profiling.

Pier 9 Shaft C of the Northbound Bridge was excavated using a 9.84-foot outside diameter digging casing that was installed using a casing oscillator. This temporary digging casing was installed over the full length of the excavated borehole. Soil was excavated using a spherical hammer grab and ground water pressures were counterbalanced by introducing water inside the temporary casing. The reinforcing cage measured 8.5-feet in diameter and was installed to a depth of approximately 1-foot above the base of the shaft. The reported volume of concrete placed exceeded the theoretical volume by approximately 2.5%.

4.1 Results

The thermal results presented are based on the data from 10 Thermal Wire cables attached to the full length of the shaft's reinforcing cage. Peak temperature for Pier 9 Shaft C was reached approximately 46.5 hours after concrete placement. The thermal analysis and radius estimation was performed at the time of peak temperature. The measured Temperature (degrees Fahrenheit) vs. Elevation (feet) is presented in Figure 7. The temperature data recorded by the individual wire positions around the perimeter of the cage are presented by the colored profiles while the average of all local temperature measurements is presented in the bold black profile.

Prior to processing the data using the TIP-Reporter Software, a qualitative assessment of the collected data may be performed. For Pier 9 Shaft C the top of shaft roll-off in temperature appears normal and is caused by an increase in surface area at the top extent of the shaft. Temperature roll-off at the base of the shaft is also observed due to an increase in surface area at the bottom extent of the shaft. The temperature profile appears uniform from the top of the shaft down to EL.-78. The obvious characteristic that stands out is the significant reduction in the temperatures recorded in all ten cables at elevations of approximately -80 to -95 feet. The lowest recorded temperatures were near Wires 7, 8, and 9 where the local recorded temperatures were approximately 35 degrees Fahrenheit less the average temperature of the shaft both above and below this region. The data also shows evidence that the cage may have shifted slightly and the rebar cage may not be concentrically located within the shaft.

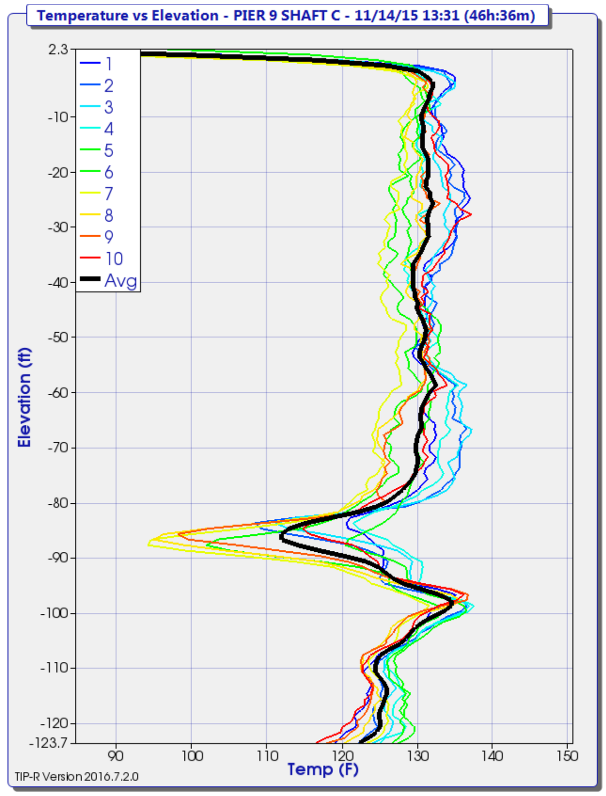

Figure 7. Temperature vs. Elevation

An assessment of shaft radius was performed once the volume information was added and the roll-off adjustments were performed. Figure 8 presents the Effective Average Radius (inches) vs. Elevation (feet) and the Effective Local Radius vs. Elevation (feet) based on the reported concrete volume and the reported cage radius. The Effective Local Radius is the computed radius from the measured data at the individual wire locations while the Effective Average Radius is the computed average radius at a given depth based on the average of all recorded local temperatures. The vertical dashed green line represents the design or intended shaft diameter, in this case the outside diameter of the temporary casing was used. The vertical dashed red line represents the edge of the reinforcing cage. Figure 8 also presents the estimated cover beyond the reinforcing cage on the bottom x-axis.

From the top of shaft to EL.-78 the Effective Average Radius is slightly greater than the design shaft radius of 59.04-inches. This slightly oversized region is consistent with the reported concrete over pour. Beginning at EL.-78 the Effective Average Radius reduces down to 52-inches near EL.-85.70. The Effective Local Radii reduce to approximately 44 to 45-inches near Wires 7 and 8 at EL.-85.70. An increase in cover or excess concrete is evidenced by higher recorded temperatures near EL.-98. The Effective Average Radius is relatively consistent with the design radius from EL.-106 to the base of the shaft.

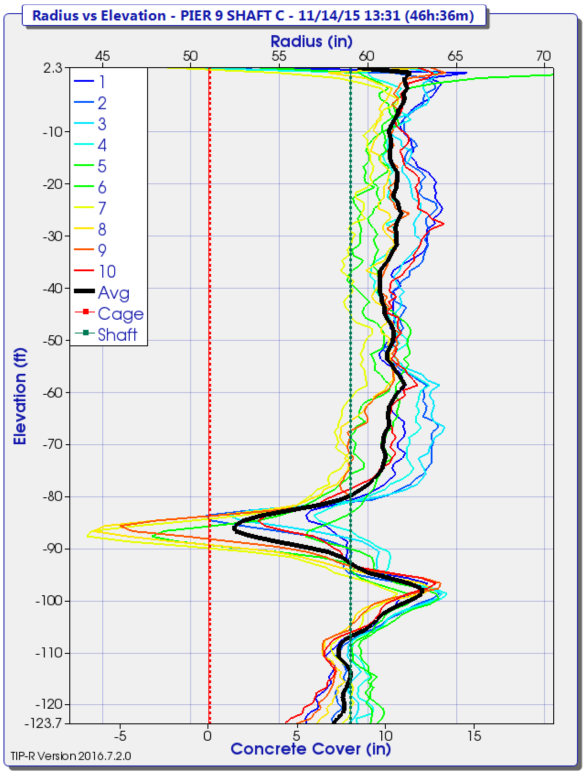

Figure 8. Effective Radius vs. Elevation

The soil profile with an overlay of a 3D model of the shaft is presented in Figure 9. The 3D model is rotated to where the position of Wires 7 and 8 are on the left side of the image and Wires 2 and 3 are on the right side. The reinforcing cage is displayed as well as the estimated shaft shape based upon the calculated local radii. At EL. -87 the cage is visible near Wires 7, 8, and 9 which indicates there is no calculated concrete cover in this region. A reduction in the projected concrete cover is also observed near Wires 3, 4, and 5 however the model is not showing the reduction down to the reinforcing cage.

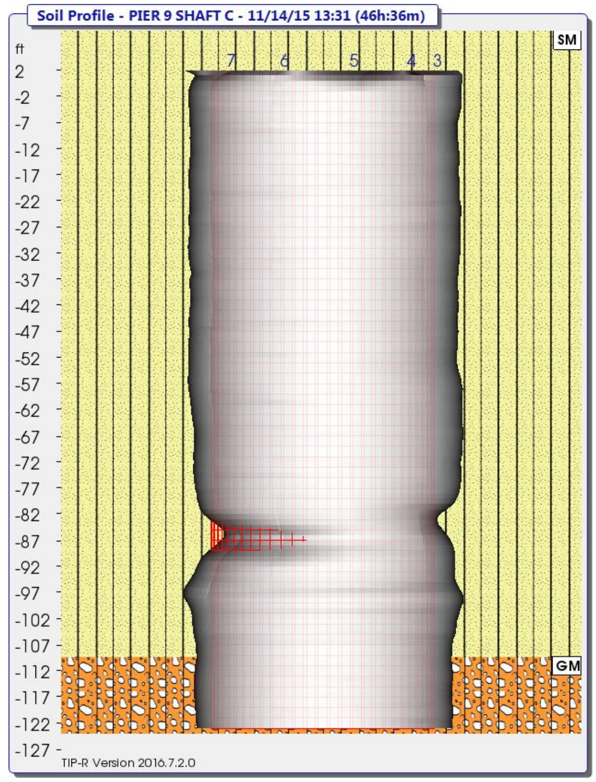

Figure 9. Soil Profile with Overlay of 3D Model

4.2 Exploratory Coring and Remediation

Due to the estimated reduction in radius to inside the reinforcing cage, the shaft was cored to try to locate the extent of the anomaly. Since coring outside the cage is in most cases not feasible, the first core was reportedly drilled 18-inches inside the reinforcing cage between Wires 7 and 8. This location was selected due to Wires 7 and 8 showing the maximum reduction in radius. The core was angled slightly so that near EL.-87 the core would be in close proximity to the cage. The core taken at this depth is shown in Figure 10.

Figure 10. Core from Pier 9 Shaft C near EL.-87

The core revealed a segregated or washed out region of concrete in the shaft near EL. -87. When compared to the TIP model, these results correlate exceptionally well. When viewing the Effective Local Radius vs. Elevation plots, the vertical extent of the contaminated region inside the reinforcing cage appears to be approximately 1-foot near the location of Wires 7 and 8. The core sample taken from this region confirmed these results. It was reported that additional cores were taken to determine the radial extent of the segregated region. Cores taken near the center of the shaft and diametrically opposite of the core taken near Wires 7 and 8 revealed good quality concrete which also correlates well with the TIP model. Once coring was completed, it was reported that the cored holes in the shaft were inspected with a camera and then hydro-blasted, and pressure grouted.

5 CONCLUSIONS

TIP has gained wide acceptability in the foundation engineering and construction communities throughout the world. TIP testing is being used more frequently for integrity assessment of drilled shaft and ACIP piles due to the advantages this test method has when compared to other available test methods. As shown in the examples in this paper, TIP testing can effectively provide more information than what can be obtained from a combination of three other testing methods (Caliper, CSL, and GGL), including a quality assessment of the entire cross-section, the as built shape and local radii of the shaft, as well as the relative position of the reinforcing cage within the excavated hole. An additional benefit of the TIP testing method is the time savings that can be gained from the use of this technology. The TIP is utilizing the naturally occurring heat of hydration from the curing cement which begins soon after the shaft is cast. The TIP test can typically be completed within 8 to 24 hours after casting, allowing for an earlier shaft assessment than is possible with any other testing method and allowing for an accelerated construction process. TIP testing does not have many of the limitations associated with other integrity testing methods. TIP testing generally results in more integrity information than can be obtained with any other integrity testing method, and these TIP results are obtained in less time than can be obtained from any other integrity testing method.

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