THERMAL INTEGRITY PROFILING ACCELERATES CONSTRUCTION OF RAILROAD PROJECTS

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Body of Paper - 2,676 Words

Abstract:
Railroad bridge projects are often subject to demanding schedules with limited outage windows. Cross-hole Sonic Logging (CSL) is the most common test method to assess the integrity of drilled shafts. However, the minimum age of concrete, or elapsed time after placement, for testing is three days per ASTM recommendations, and generally five to seven days for larger shafts. Thermal Integrity Profiling (TIP) is a non-destructive testing technology that utilizes the temperature generated by curing cement (hydration energy) to assess the quality of cast in place concrete foundations. The results can be analyzed once the shaft reaches peak temperature, generally one or two days after placement. TIP models the effective shaft radius, shaft shape, and concrete coverage beyond the reinforcing cage, including the alignment of reinforcing cage. On two recently completed railroad projects CSL testing was specified and replaced by TIP testing in order to meet rigid construction schedules. Both satisfactory and anomalous shafts were observed. Results from both projects are presented along with a case history from a DOT project where a defect was detected by TIP and confirmed via exploratory coring.

INTRODUCTION

Due to the nature of drilled shaft construction, visual inspection of the final product is difficult to assess. Therefore, drilled shafts are commonly subject to some form of testing to assess integrity. The demand for testing on railroad bridges has been increasing in recent years as designers recognize the importance of shaft integrity testing. Optimum performance of the shafts is critical; railroad bridges frequently have lower shaft quantities, thus less redundant foundation elements, as compared to highway bridges. However, the paramount demand for railroad bridges is time due to strict constraints associated with outages for construction.

Current options for state-of-practice integrity testing methods are few in number. As with the entire drilled shaft practice, the most commonly specified testing method is Cross-hole Sonic Logging (ASTM D6760), or CSL. With increasing frequency, the designer or the contractor is replacing CSL testing with Thermal Integrity Profiling (ASTM D7949), or TIP. There are advantages and disadvantages to both testing methods, but the driving force for TIP testing in the railroad industry is the time within which the analysis can be completed. A brief review of the testing methods is described below.

CSL TESTING

Cross-hole Sonic Logging is performed via steel access tubes tied to the inside of the shaft reinforcing cage. Per the ASTM specification, one tube should be installed for every foot of shaft diameter. A transmitter probe and a receiver probe are raised or lowered together in the tubes with an electronic pulse generating from the transmitter. The arrival time and the strength of the signal, presented as a function of depth, are indicative of the uniform nature of the concrete between the probes. Generally, the First Arrival Time, also referred to as FAT, is considered the more reliable measurement. All of the tube combinations, or profiles, are tested over the full shaft length. Assessing the sum of the data allows for delineation of areas of reduced concrete quality. Performing the test in the field is straightforward and the results are clear to understand. The results of the test are limited, however, to the concrete located between the transmitter and the receiver, which covers most, but not all, of the shaft area within the cage. No assessment of concrete beyond the tubes, i.e. concrete cover, can be made with CSL results. The other significant limitation is the wait time between shaft placement and testing. The ASTM specified minimum time to test is three days, for shafts greater than 4 feet the results are often improved five to seven days after placement.

TIP TESTING

Thermal Integrity Profiling is performed via Thermal Wire® cables which are zip tied to the inside of the reinforcing cage prior to placement. As with CSL, one cable should be installed for every one foot of shaft diameter. The cables contain a digital temperature sensor located along every one foot of the instrumented wire length. Upon placement of the concrete the wires are connected to data collectors which take a temperature reading at each node every 15 minutes. Once the shaft has achieved peak temperature, generally 20 to 30 hours after placement, the data is suitable for analysis. The collected data is then aggregated in the TIP analysis program. This allows the TIP engineer to view the entire concrete temperature cycle, which allows for a visual assessment of areas of concern. Prior to generating the radius assessment, the raw data must be normalized at both the top and bottom of the shaft. The shaft ends require an adjustment to account for the convective heat loss to the ambient air above the shaft (e.g. top of shaft roll-off) and for the conductive heat loss to the soil or rock at the base of the shaft (e.g. bottom of shaft roll-off). The estimated radius is based on a temperature to radius relationship, which is based on the average temperature recorded and the placed concrete volume over a given length. The final outputs presented are the Temperature vs. Depth plots, the Effective Average Radius vs. Depth plots, and a 3D representation of the shaft radius. The alignment of reinforcing cage can also be evaluated by comparing temperatures at opposite locations on the cage for a given depth.

COST & SCHEDULE

The total cost to perform CSL and TIP testing are approximately equal for small to medium sized projects. The main cost for either test method is the testing medium, steel tubes for CSL testing or Thermal Wire® cables for TIP testing. CSL requires time in the field to perform the tests, which can be significant for larger shafts. TIP testing minimizes the effort in the field but relies on detailed field inspection, particularly the placed concrete volume information.

Accelerated schedules and costs savings may be recognized by a project by utilizing Thermal Integrity Profiling to assess the integrity of shafts. Accelerated schedules are a direct result of the information required for analysis being available sooner than with other integrity test methods. One of the latest developments in TIP testing allows the user to monitor the temperature data in real-time using a cloud based cellular platform. This real-time monitoring of the data allows for permissioned users to gain access to the data on demand. The TIP engineer can monitor for peak temperature from a remote location and provide an immediate assessment of the results.

In order to perform CSL testing, steel access tubes are cast into the foundation element. After CSL testing is complete, post grouting of the access tubes is required in most cases. This step can be eliminated if the access tubes are eliminated from the shaft. Post construction requirements for Thermal Integrity Profiling involve cutting the cable at the top of shaft. Alternatively, if long term temperature monitoring is of interest, the cables could be routed to an accessible location and monitored at a later time.

CASE STUDIES

Case 1

The first case presented is from a two span railroad bridge in north-central Illinois. The bridge had one pier, which was supported by three – 6 foot diameter shafts with 5 foot diameter rock sockets. The shaft lengths ranged from 21 to 29 feet and the rock sockets ranged from 8 to 12 feet in length. The soil overlying the bedrock generally consisted of layers of clay over dense sand and gravel and the bedrock consisted of inter-bedded limestone and shale.

Initially CSL testing was specified on the shafts. TIP testing was approved as an acceptable substitute to assess the integrity at the contractor's request in order to accelerate the shaft construction schedule. The cages were instrumented with TIP wires and the shafts were placed in one day. For all three shafts the data was collected from the end of concrete placement through the day following placement, at which time the concrete had reached the peak temperature. Rapid collection and transmission of the data to the responsible TIP engineer allowed for a preliminary review of the TIP data on that same day. One of the shafts (#2 – Center) indicated a reduction in effective average radius near the base of the shaft. The TIP results allowed for a quantifiable analysis of the reduction at the base of the shaft by the engineer of record. The following day the final report was issued and ultimately, the TIP results indicated the shaft integrity was as expected and acceptable for all three shafts. Figures 1, 2, and 3 present the Effective Radius versus Depth plots for shafts 1, 2, and 3, respectively.

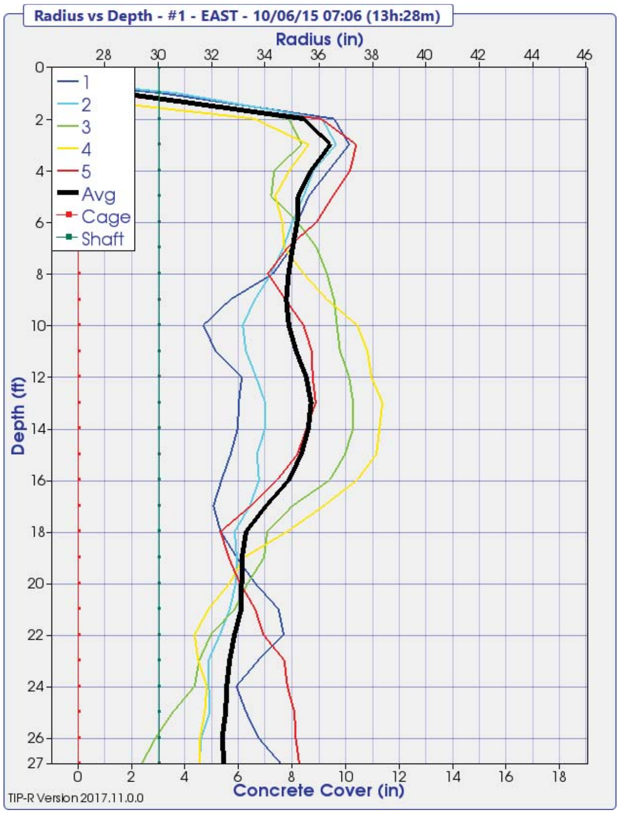

Figure 1. Radius vs. Depth Plot: Shaft #1 - East

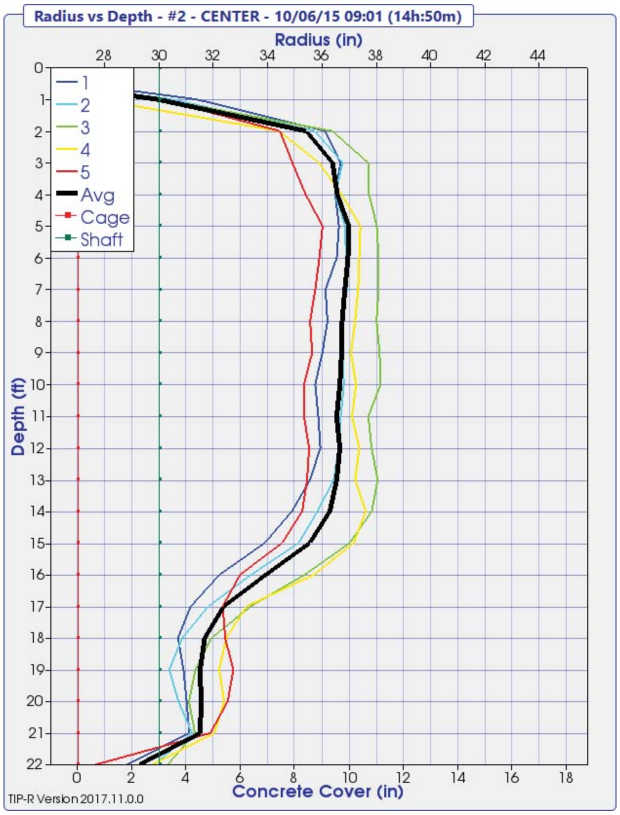

Figure 2. Radius vs. Depth Plot: Shaft #2 - Center

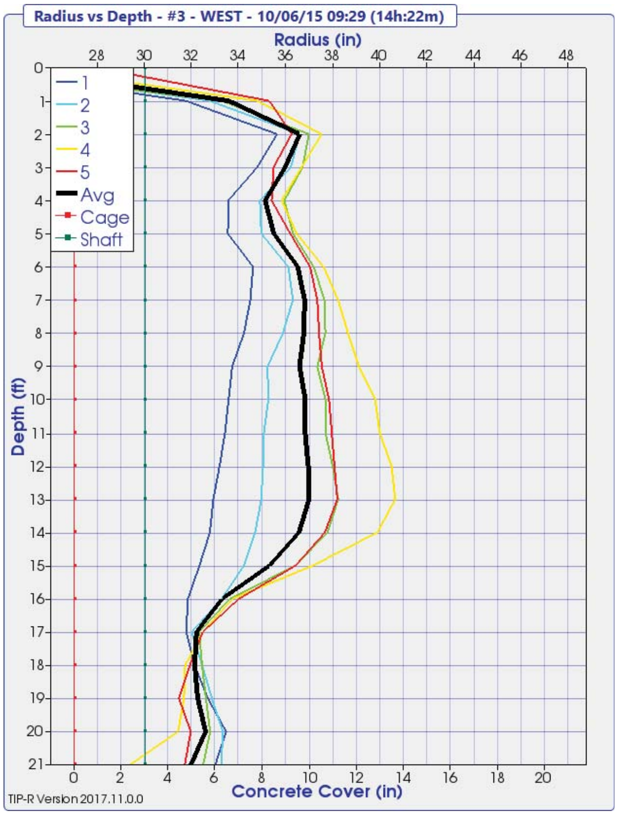

Figure 3. Radius vs. Depth Plot: Shaft #3 - West

Case 2

A four span bridge in northwest Illinois had a comparable construction sequence to that of Case 1, with CSL originally specified for integrity testing of the shafts and TIP as an accepted alternative due to time constraints. The piers were each supported by two – 5.5 foot diameter shafts with 5 foot diameter rock sockets. The shaft lengths were approximately 35 feet and the rock sockets ranged from 11 to 13 feet in length. The soil overlying the bedrock generally consisted of medium stiff clay and silt layer and the rock consisted of hard dolomite.

The shafts were excavated and placed over a span of three consecutive days, with the concrete placement process occurring over the final two days. At Bent 4, the shafts were over-drilled by approximately seven feet and the reinforcing cages were suspended. Based on the shaft diameter and the magnitude of the over-drilling relative to the bottom of the instrumented reinforcing cage, there was no bottom roll-off evident in these shafts. For either TIP or CSL testing, meaningful analysis terminates at the bottom of the instrumented cage, limiting the results to this location. A representative model of the Effective Radius vs. Depth plot for Bent 4 is presented in Figure 4.

The shafts located at Bent 2 were excavated and concreted on the same day. This is an ideal construction schedule for drilled shafts since the duration the borehole is left open is limited. The TIP results indicated the shaft integrity was as expected and acceptable for both shafts. A representative model of the effective radius vs. depth plot for Bent 2 is presented in Figure 5.

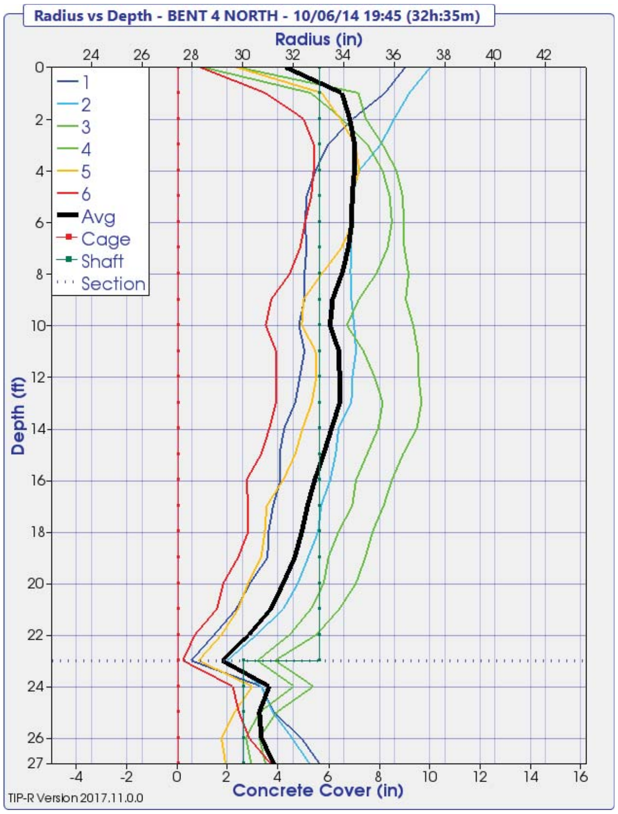

Figure 4. Radius vs. Depth Plot: Bent 4 North

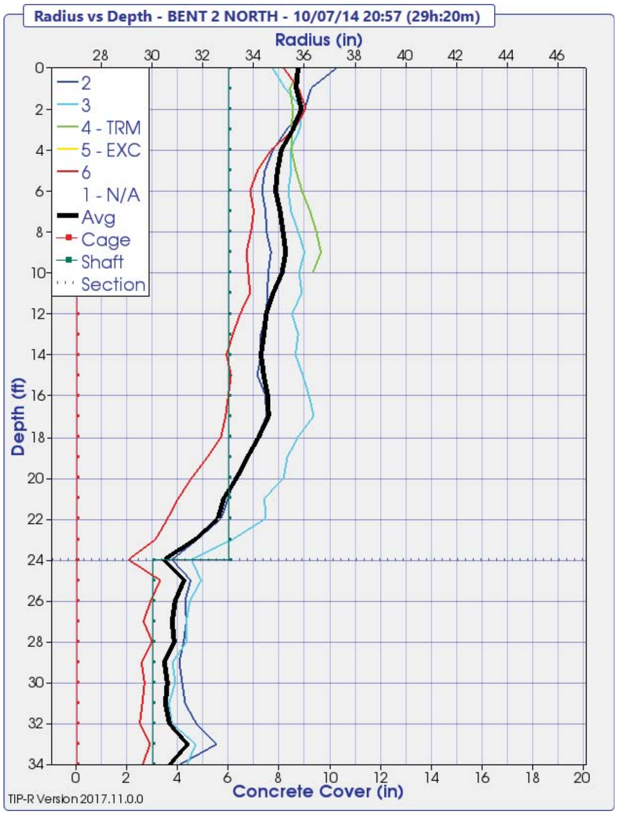

Figure 5. Radius vs. Depth Plot: Bent 2 North

Due to inclement weather and construction sequencing issues, the excavations at Bent 3 were left open for more than a day prior to placement and were poured without a final cleanout. The TIP engineer performed a field review of the data the day after these shafts were drilled, which was indicative of a severe issue for both shafts. Figure 6 presents the temperature and radius vs. depth plot for a representative Bent 3 shaft. The bottom roll-off normally occurs within the lower one shaft diameter; in the case of this shaft a bottom roll-off is apparent beginning approximately 11 feet above the shaft toe. The temperature in the lower three feet of the cage is approximately equal to the soil temperature 24 hours after placement. The TIP radius versus depth model indicates a reduction in effective radius beginning at 22 feet below the shaft top, with the effective radius less than the cage radius at 26 feet. Shortly after placement of the shafts the final TIP results were presented to the engineer of record.

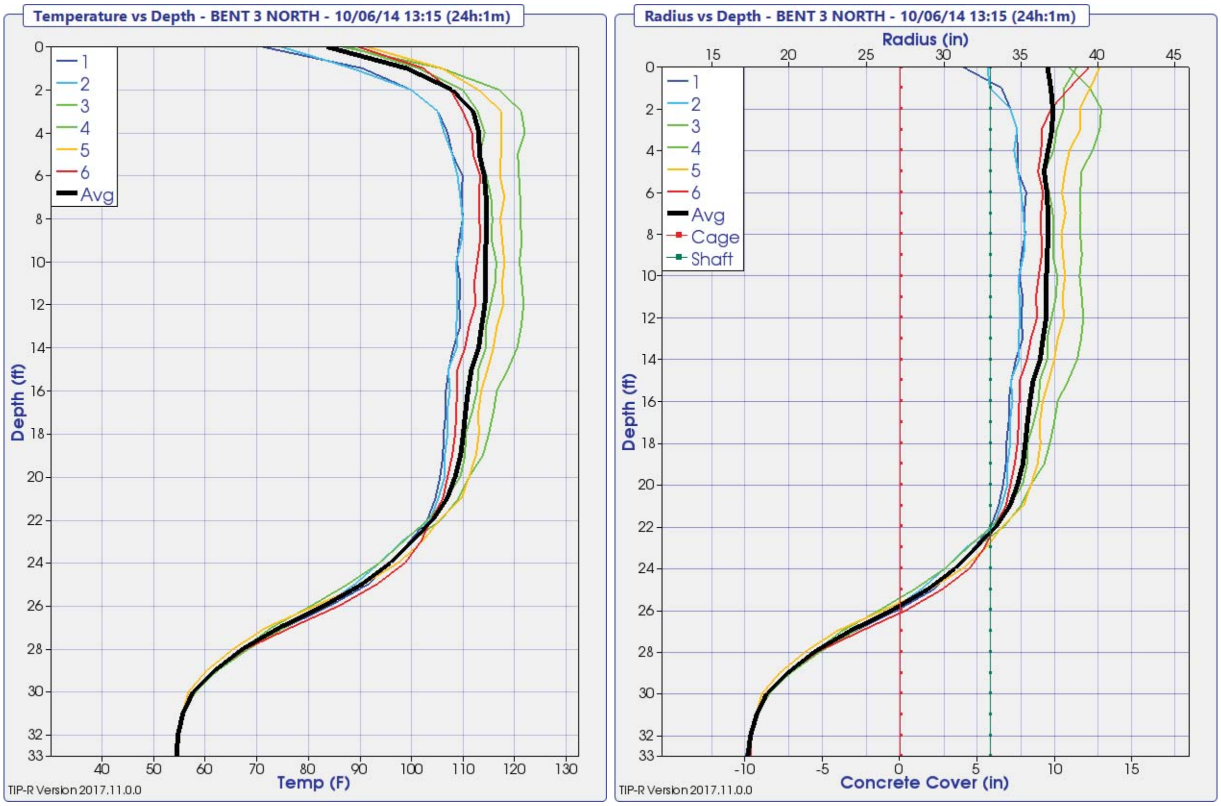

Figure 6. Temperature and Radius vs. Depth Plot: Bent 3 North

Overall, a distinct difference in the temperature profile was apparent between the shafts that were left open for days without a final cleanout versus that the shafts that were excavated and placed in the same day. It is likely that sediment built up over the course of a few days caused contamination or reduced quality concrete at the base of the shaft. A remediation plan was discussed and put into action before the shafts would have sufficient curing time for CSL testing. Ultimately, the Bent 3 shafts were replaced with driven piles.

Case 3

The final case presented is from a DOT bridge project in Tacoma, Washington with Thermal Integrity Profiling used to evaluate the drilled shaft integrity. The installed shaft was approximately 9.8 feet in diameter and contained a reinforcing cage that measured 8.5 feet in diameter. The subsurface conditions consisted of 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. The reported volume of concrete placed was approximately 102% of the theoretical volume.

The evaluation of the thermal results was based on data from 10 Thermal Wire® cables installed equidistantly around the reinforcing cage. Data was recorded from the beginning of concrete placement until peak temperature was reached approximately 46.5 hours after placement. The data was then downloaded for analysis. Figure 7 presents the Measured Temperature vs. Elevation and the Effective Average Radius vs. Elevation plot.

The temperature profile appears uniform from the top of the shaft down to EL-78 and from EL -105 to the base of the shaft. A significant reduction in temperature was observed from EL -80 to EL -95 which is indicative of reduction in the effective radius. While data from all 10 cables recorded a reduction in this region, the lowest recorded temperatures were near Wires 7, 8, and 9 where the local recorded temperatures were approximately 35 degrees Fahrenheit less than the average temperature of the shaft. Beginning at EL-78 the Effective Average Radius reduces down to 52 inches near EL-85.70. However, the Effective Local Radii for Wires 6, 7, 8, and 9 reduce to approximately 45 inches, which equates to no cover beyond the reinforcing cage in this region. An increase in cover or excess concrete is evidenced by higher recorded temperatures near EL-98.

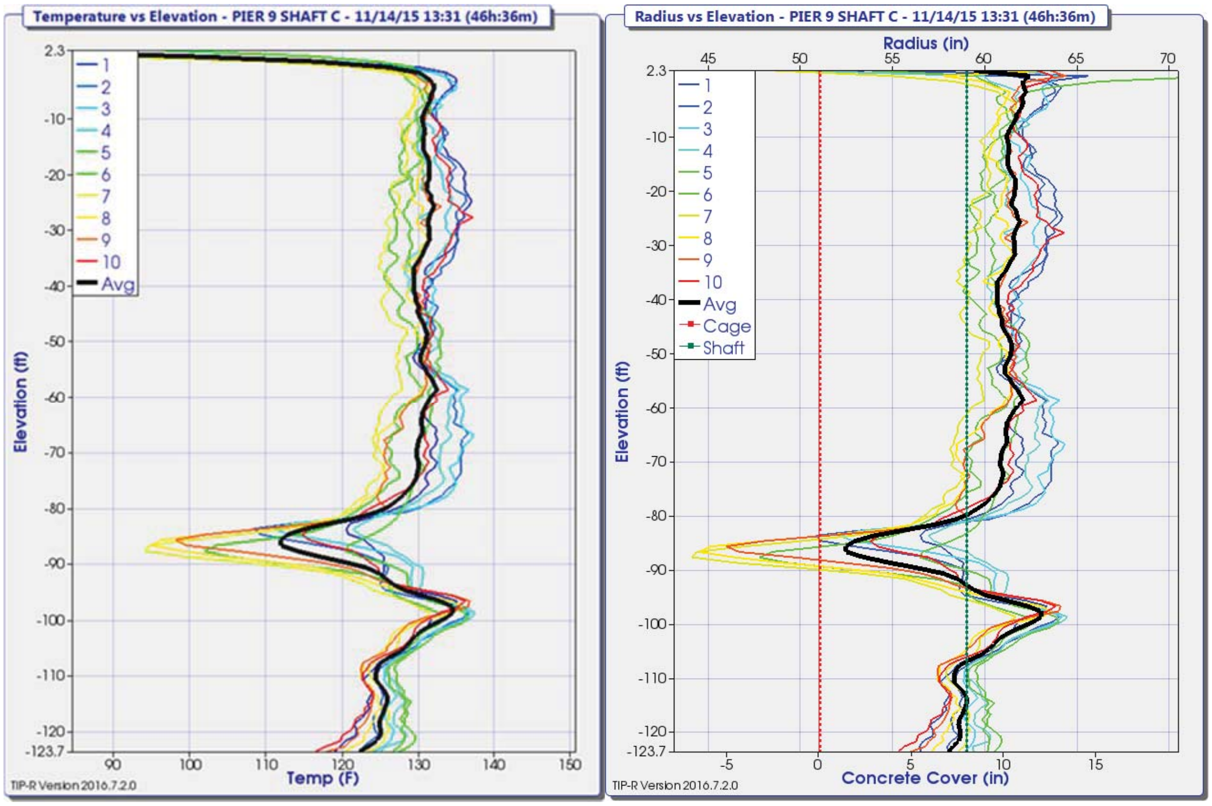

Figure 7. Temperature and Effective Radius vs. Elevation

The soil profile with an overlay of a 3D model of the shaft is presented in Figure 8. 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. 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.

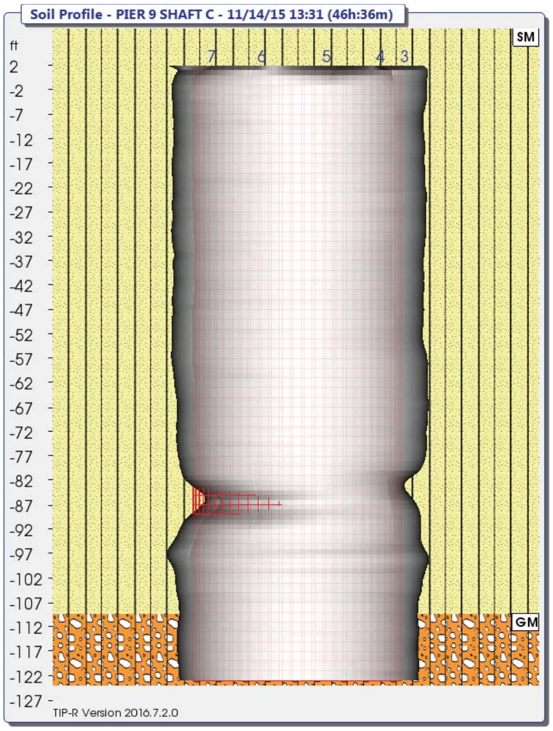

Figure 8. Soil Profile with Overlay of 3D Model

Exploratory coring was conducted in an attempt to locate the anomaly indicated by the reduction in radius within the reinforcing cage. The reported core sequence and locations are presented in Figure 9. It was reported that the first core location was approximately 6 inches inside the reinforcing cage and the core was advanced to near EL -87. Results from the core are presented in Figure 10 where a zone of segregated or washed out concrete was revealed. Three additional cores were sampled to view the radial extent of the anomalous zone.

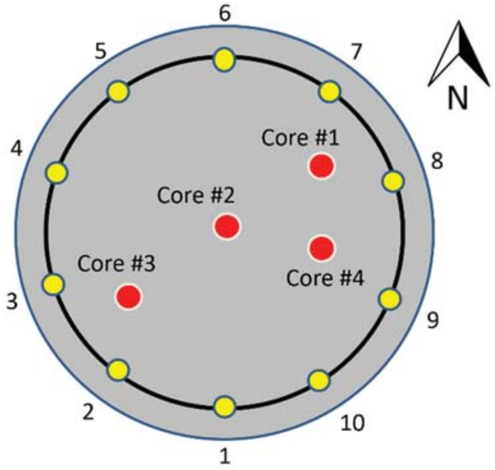

Figure 9. Exploratory Core Locations

Figure 10. Results from Core #1 near EL-87

When compared to the TIP model, the results of coring correlate well. Core #2, taken at the shaft center, and Core #3, taken near Wires 2 and 3, revealed quality concrete. Core #4 revealed contaminated concrete which was expected based on the TIP Model 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. 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.

CONCLUSIONS

Railroad Bridge projects are often subject to demanding construction schedules where accelerating the time to completion is critical. Timing and scheduling is especially critical when construction takes place during track outages. Thermal Integrity Profiling is a relatively new non-destructive integrity test method that utilizes the heat generated by curing cement to assess the quality of drilled shafts. The temperature measurements, along with placed volume and installation details, are used to model the Effective Shaft Radius, shaft shape, and concrete coverage beyond the reinforcing cage.

Several TIP projects were presented, including two railroad and one DOT bridge foundation case studies. For both railroad case studies, the project specifications called for the conventional CSL test as the primary integrity test method. The specifications were subsequently amended to replace CSL with TIP to allow for accelerated foundation construction schedules. Anomalies were identified in a timely manner accommodating remedial efforts sooner than what would have been recognized with CSL testing. Additionally, TIP identified an anomaly on a DOT bridge foundation where exploratory coring confirmed the presence of a deficiency. The accuracy of the test, along with the compressed time frame for test results, make Thermal Integrity Profiling an effective testing method for integrity testing of foundation elements in the rail road industry.

Thermal Integrity Profiling Accelerates Construction of Railroad Projects

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Why should we test drilled shafts?

Major defects can lead to foundation failures

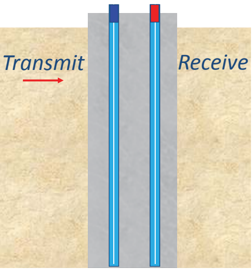
Outline

- Current State-of-Practice Methods
  - Cross-hole Sonic Logging (CSL)
  - Thermal Integrity Profiling (TIP)
- Cost & Schedule on Railroad Projects
- Case Studies
  - Accelerated Railroad Project Schedule
  - Defective Railroad Project Shaft
  - WSDOT Core and Confirmed Defect

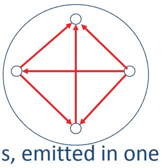
Cross-Hole Sonic Logging

Cross Hole Sonic Logging

ASTM D6760-02



Plan view of shaft with 4 access tubes



Sonic Waves, emitted in one tube are received in another if concrete quality is satisfactory

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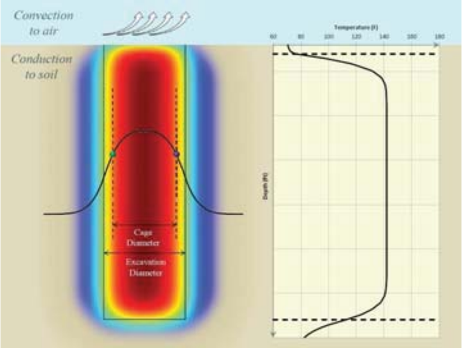
Cross-Hole Sonic Logging

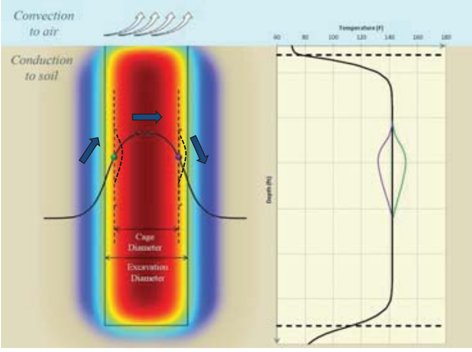
- Advantages
  - Evaluates concrete quality inside cage
  - Provide results by depth and by quadrant
  - Tomography available for complex cases
  - Large testing window, repeat tests can be performed
- Limitations
  - Wait a minimum of 3-4 days prior to testing
  - Requires access tubes and post grouting
  - Cannot evaluate concrete cover
  - Debonding and bleed water may lead to unnecessary coring

Thermal Integrity Profiling

TIP Overview

- Heat generated by curing cement is measured and used to assess integrity
- Increases in temperature correspond to increases in concrete cover (bulge)
- Decreases in temperature correspond to contaminated or reduced quality zones
- Cage Alignment assessed by viewing diametrically opposite cables

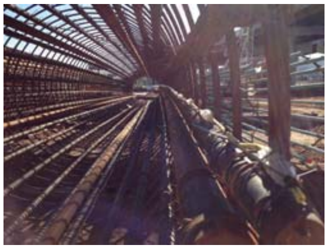




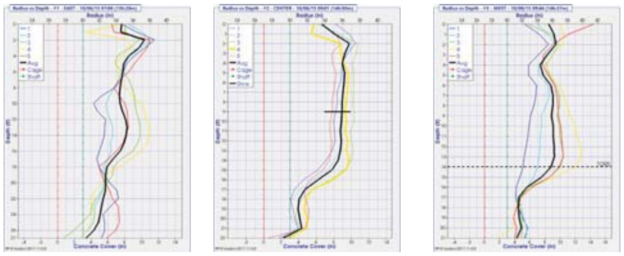
Thermal Integrity Profiling

- Advantages
  - Evaluates full shaft cross section, including cover outside reinforcing cage
  - Evaluates cage alignment
  - Accelerated project schedules
  - Results available 20-30 hours after placement
  - Insensitive to debonding
  - Access tubes eliminated
- Limitations
  - Early testing window (early in hydration process)
  - Cables lengths require pre-planning
  - Requires detailed installation records including the concrete volume placed

Case Study: TIP as a Substitute for CSL Railroad Bridge



Effective Radius for Shafts 1, 2, and 3



Case Study: TIP as a Substitute for CSL Railroad Bridge

Effective Radius for Bent 2