Structural Evaluation of Thermal Integrity Profile Results of Transmission Foundations

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ABSTRACT

The drilled shafts that support transmission lines and substations have been increasingly subject to testing to assess the integrity of placed concrete. Cross-hole Sonic Logging (CSL) has been used, but large diameter shafts with challenging site access are generally more favorable to Thermal Integrity Profiling (TIP) testing. TIP testing assesses the shafts based on measurements of the concrete temperature during curing. The TIP results provide assessment of integrity both within and outside the cage, along with information about the alignment of the cage and concrete cover. This data has allowed shafts with imperfect results to be subject to more detailed structural evaluations. However, it may not be well understood how to use this additional information by designers and engineers. The purpose of this paper is to present TIP results of transmission line foundations, both with and without issues with integrity, including cage shifting, minimal concrete cover, or soil inclusions. The intent is to provide general guidelines of the issues that merit additional investigation and those that should be recognized as inconsistencies inherent to underground construction.

KEYWORDS

Shaft Integrity, Thermal Integrity Profiling, TIP, Transmission Line Foundations

BACKGROUND

This paper is intended to discuss some of the drilled shaft evaluations made when TIP testing is performed. The authors of this paper were recently involved with a transmission line project that was designed and constructed for a Confidential Utility Client located in the Midwest United States. The project was delivered as an Engineering, Procurement, and Construction (EPC) contract with the electrical line construction company as the prime contractor. The contractor then subcontracted several parts of the work which included engineering for transmission line and foundation design, foundation construction, and third-party testing intended to evaluate the concrete homogeneity and integrity of the place concrete in the deep foundations. The testing method selected was Thermal Integrity Profiling Method B, which uses thermal sensors embedded in the concrete. The TIP testing was administered by Mr. Travis Coleman with GRL Engineers, Inc. Mr. Ryan Weaver with Burns & McDonnell served as the owner's engineer and technical consultant for the utility and was responsible for reviewing submitted TIP reports and providing recommendations to the utility on their acceptance, and if there were any issues that would warrant further discussion and analysis.

The utility specified a significant number of structures requiring TIP testing. The foundations tested were at all line deadend locations, any line angle structures that exceeded 3-degrees, and approximately 10% of the remaining structures, which were selected at regular intervals or at areas of interest (e.g. near waterways) along the transmission line route. In additional to the contractor's own administered quality control program, TIP testing was heavily relied upon to help ensure the foundation construction consistently utilized best practices, and provided the utility with information that the foundations were installed with as-expected concrete homogeneity, met specified concrete cover requirements, etc. The transmission line consisted entirely of steel monopole structures, and the nominal sizes of the drilled pier foundations varied from 5.5-ft in diameter and 15-ft in embedded depth up to 13.5-ft in diameter and 59-ft in embedded depth.

DESIGN OF TRANMISSION LINE REINFORCED CONCRETE DRILLED PIER FOUNDATIONS

Design of these types of foundations involve both the analysis of the pier-soil interaction and then the structural reinforcement design of the concrete section. The piers are considered as "beams" and are typically subject to high bending moments applied at the top of the pier. Pier to soil interaction generally doesn't rely on end bearing, but rather on lateral resistance of the soil which can be modeled using non-linear springs. The springs represent the ultimate soil passive pressure but can also include vertical side shear and base shear. Satisfactory lateral design of a drilled pier foundation requires that the ultimate capacity of the foundation must exceed the maximum expected applied loads and that the groundline deflection and rotation for design loads must remain within serviceable limits.

Typical design programs used are EPRI's Foundation Analysis and Design (FAD) Tools, which is an industry-specific program that is administered by DiGioia Gray & Associates, and LPILE by Ensoft, Inc., which is also a special-purpose program used for analyzing a single pile (or drilled shafts) under lateral loading using nonlinear lateral load-transfer (*p-y*) curves. Other internal design tools may be used as well, especially for reinforcement design, but these two programs are the most widely used in the Electric Power Transmission and Distribution industry. It should be noted that neither of these programs or ACI-based spreadsheet calculations account for situations where cage shift has occurred during construction.

TIP TESTING

TIP testing is based on the measurement of temperature as the concrete cures following placement. Determining the shaft's temperature to volume relationship allows for modeling of the effective radius of the shaft, including any bulges or reductions due to inclusions or reduced quality concrete. Additionally, diametrically opposite locations provide information on the alignment of the cage relative to the excavation and the concrete cover. The Thermal Wires® are tied along the full reinforcing cage length, and are equally spaced with a frequency of one wire per foot of diameter, with a temperature node every one foot of embedded wire length. Shortly after shaft placement, the Thermal Wires are attached to data logger boxes, and the temperature at every node is recorded every fifteen minutes. This allows for review of the shaft concrete temperature shortly after placement, increasing up to a peak shaft temperature, and then decreasing as the heat continues to dissipate into the soil. Analysis generally occurs at or slightly before the shaft reaches its peak temperature. The analysis is performed based on a relationship between the average temperature measurements and the placed concrete volume. Additional corrections must be made for the top and bottom roll-off, the zones where additional heat is dispersed longitudinally to the air and soil at the base of the shaft. These corrections are performed based on concrete, soil, and air temperatures at the time of analysis and the time for the concrete to reach peak temperature. Following these corrections, the results are presented as effective shaft radius, shown versus depth. The purpose of the term "effective" is to express that TIP results do not delineate between soil inclusions and reduced quality concrete.

PROJECT PROTOCOLS

For the shafts on this project, the typical shaft report submittal included the following items:

- Inspection field reports, which provided the as-drilled shaft dimensions, location of any temporary or permanent casings installed, depth at which the water table was encountered, depth to any rock layers that may have been encountered, use of water of drilling slurry used to maintain head pressure on the excavated hole, time and duration of both hole drilling and concrete placement, concrete strength and slump field testing data, specific locations of the TIP wires, and other items of interest from the construction of the shaft foundation.
- The TIP report with comments and recommendations provided by the TIP engineer.
- A cover letter by the design engineer indicating they had reviewed the report and also providing an opinion on any variations from the specified dimensions and placement requirements, any issues

apparent as noted either from the TIP report or the field reports, and then most often their acceptance of the installed foundation.

The owner's engineer reviewed the complete submittal. When all items appeared to be in agreement, a brief summary indicating findings and recommendation of acceptance of the shaft would be submitted to the utility. When variations were apparent, those issues would be noted along with an opinion regarding their acceptance, along with recommendations for further investigation or analysis.

A couple of items to additionally note that were unique to the construction of the foundations for this transmission line project: As part of stabilizing the upper strata of soil around the excavation, which then also assisted the foundation contractor in setting the full-length anchor bolts (which were used as the longitudinal reinforcement for the drilled pier shaft), a permanent corrugated metal pipe (CMP) casing was initially installed prior to drilling activities. This casing would then be grouted in to help fill any voids around it which then enabled appropriate soil-pier interaction to be applied in the upper layer(s) of the foundation. The use of the grouted-in CMP could influence the reported curing temperature of the pier in the upper portion of the shaft as many times the grout could still be curing when the remainder of the pier was being constructed.

REPRESENTATIVE PROJECT TIP RESULTS

<u>Shaft 1</u>

Figures 1 and 2 show a typical TIP result for a shaft without significant issues. The average radius is greater than the nominal radius over the full shaft length, with a bulge apparent in the upper portion of the shaft near the ground surface. This is typical, with oversized casings often used near the ground surface along with repeated passing of the drilling equipment during excavation. A close review of the upper 2 ft would indicate that one wire has an anomalous effective radius which is less than the cage radius 1 foot below the shaft top. The upper roll-off correction is applied to the average shaft temperature. Thus, any slight elevation changes in the first embedded node, which are circled in the temperature vs. depth figure, are exaggerated within the changes in boundary condition occurring in the shaft reveal. This limitation of the TIP results should be noted, along with a recommend to visually inspect the shaft top.

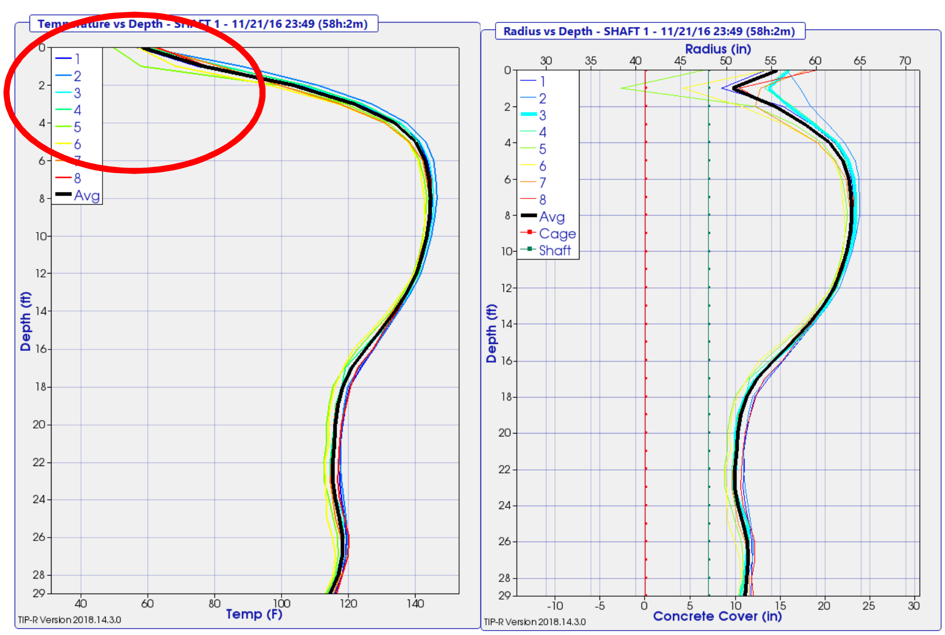

Fig. 1 and 2 – Shaft 1 Temperature and Effective Radius versus Depth

Owner's Engineer Comments: For this installation, it was apparent that the installed dimensions of the foundation were larger than the design dimensions. No further discussion was warranted for this foundation.

Shaft 2

To contrast, Figures 3 and 4 show the TIP results for Shaft 2, a shaft with clear indications of issues. Even without performing TIP analysis, an issue with the shaft is evident based on the temperature vs. depth results. A roll-off should be evident in the lower 7 ft to 9 ft of the shaft as seen at the shaft top and as projected at the shaft bottom with the dashed red line. Instead, a linear decrease in temperature is evident over the lower half of the shaft length. The average radius indicates an effective radius equal to the nominal radius at 24 ft, and less than the reinforcing cage from 28 ft to the bottom of the shaft.

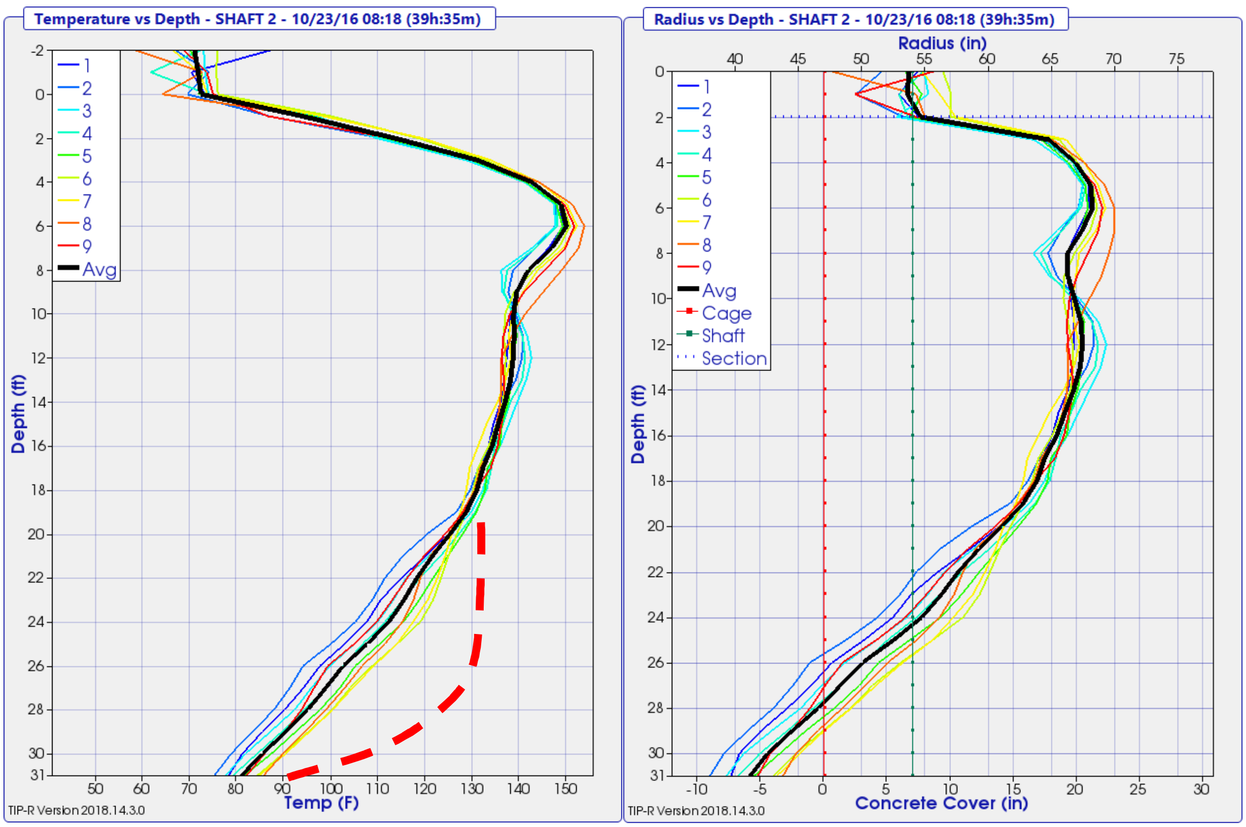

Fig. 3 and 4 – Shaft 2 Temperature and Effective Radius versus Depth

An important means of checking the data is to plot the theoretical versus placed concrete volumes, which are presented in Figure 5. While the placed concrete volume is greater than the theoretical volume in the lower portion of the shaft, the placed and theoretical volumes converge in the upper portion of the shaft. Whether the upper portion is permanently or temporarily cased, the placed volume should be at least equal to the nominal volume, as shown with the dashed line, and generally should be greater. The value of this plot is limited by the accuracy of the concrete depth measurements that can be taken in the field, but as a general rule any convergence of the theoretical and placed concrete volumes merits a closer review.

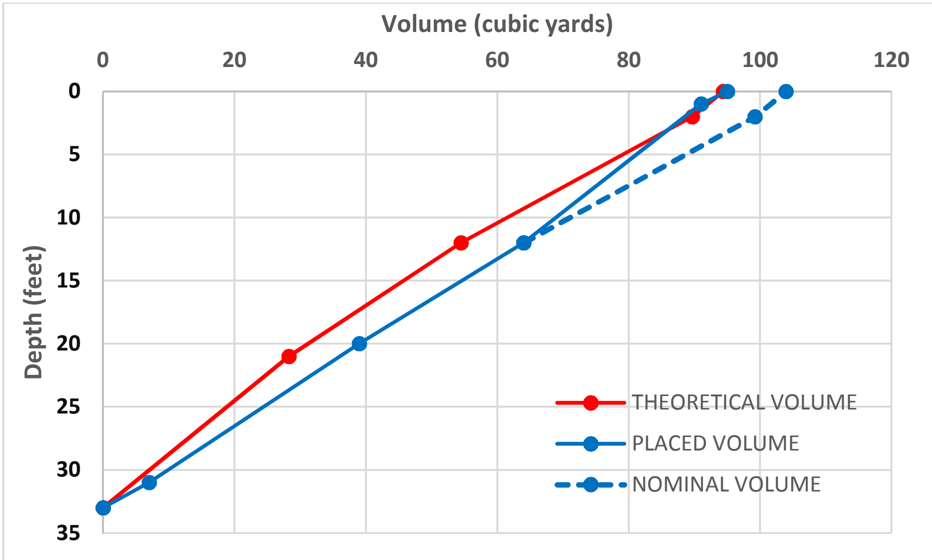

Figure 5 – Shaft 2 Theoretical Versus Placed Concrete Volume

A core was advanced outside of the bolt ring for this shaft. The core indicates concrete with sand lenses were encountered beginning at 25 ft below the shaft top. The final approximately 7 ft of the core are shown in Figure 6 below, with low concrete breaks, sand seams, and unrecoverable sections.

Figure 6 - Shaft 2 Core Results

Owner's Engineer Comments: Based on the TIP analysis and the follow-up rock coring, the design engineer further reviewed the foundation design based on revising the pier depth to be the estimated depth at where the concrete contamination became apparent, while also allowing for the larger as-constructed diameter to be included. A 9 ft diameter X 26 ft length pier design was evaluated where the initial design was for 8.5 ft diameter X 31 ft length. It was found that the revised design presented did not appear to meet the serviceability requirements (i.e. displacements), and applied loads were greater than design capacity. Ultimately the shaft was abandoned and re-drilled.

Shaft 3

Shaft 3 is an example of a shaft that required rigorous evaluation. The TIP results are shown in Figures 7 and 8. There are a number of issues to be addressed, which are noted on Figure 8 below:

1. A shift in the cage relative to the excavation. Between 27 ft and 32 ft the effective radius relative to the cage radius transitions from 16 in to 1 in in the vicinity of Wire 9. The opposite wire, Wire 3, transitions from 4 in to 13 in.
2. An area of reduced cover along one quadrant, with Wires 8 and 9 having an effective radius equal to the cage radius. These two issues indicate an eccentricity in the upper and lower portions of the excavation, as opposed to bending or sweeping in the cage, such that the lower portion of the cage is very close to face of the excavation on one side.
3. A localized reduction near the bottom of the excavation. The reduction indicates that in the vicinity of Wires 5, 6, 7, and 8 the shaft has an effective radius less than the cage radius over the lower 2 ft.

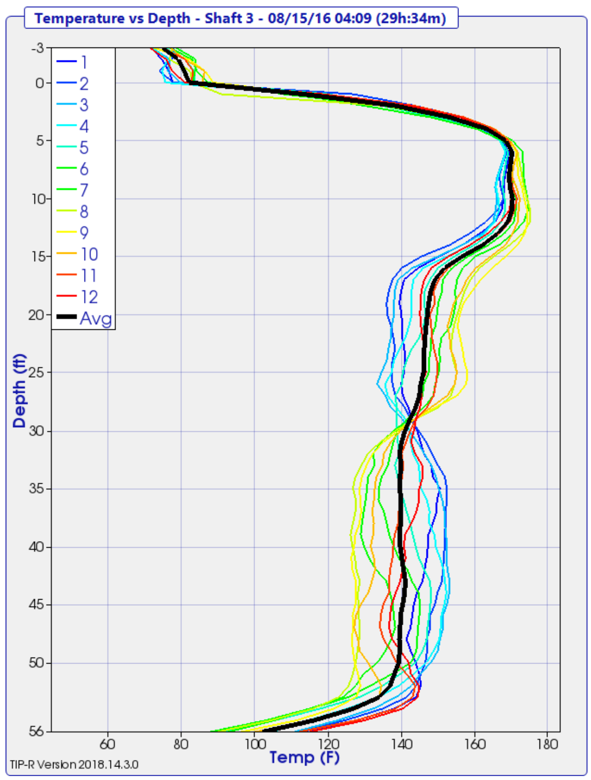

Fig. 7 – Shaft 3 Temperature versus Depth

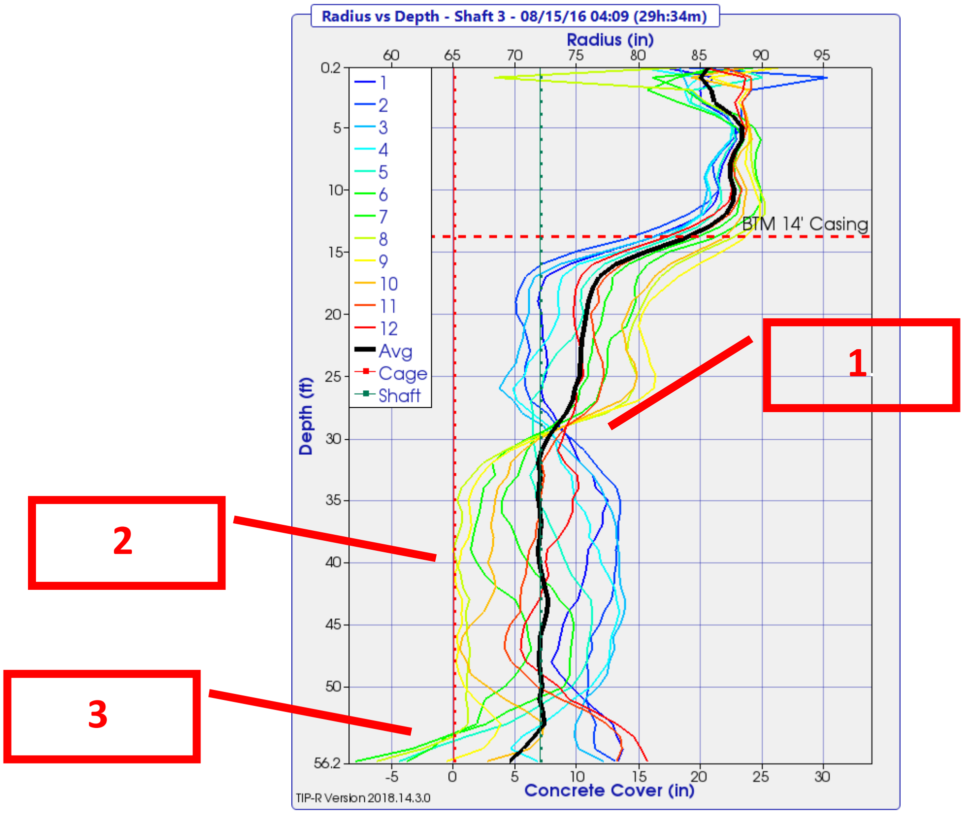

Figure 8 – Shaft 3 Effective Radius versus Depth

<u>Owner's Engineer's Initial Comments:</u> This was a significantly large shaft, with nominal design dimensions of 11.5-ft diameter X 56-ft length. The structure that is supported by the shaft is a deadend structure that is intended to support terminal line loads (i.e. line loading from only one side). This structure was located outside of the utility substation and thus would also typically handle large differential tension loading, with the line side being high tension and the substation side being low tension. Individual cross sections of the shaft at key locations were requested for further evaluation When evaluating the placement of the TIP wires, it was found that this area of insufficient cover happened to be on the compression side of the pier. See Figure 9 for the direction of the higher tension line load relative to the pier cross section at a depth of 36 ft.

There were considerable discussions on how to evaluate the pier and how the pier could be mitigated. An additional foundation analysis was performed, which also accounted for the oversizing of the upper section and as-tested higher concrete strength. Though the affected southeast/east section of the pier below a depth of 32 ft was expected to be in compression and not likely subject to tension-side loading in the pier, the highest range of expected shear was from 30 ft to 50 ft depth, with maximum shear at approximately 41 ft depth. The design engineer evaluated the shear requirements based on unreinforced concrete. The issue of shear rupture, where a significant section of the pier would be subject to high levels of shear without sufficient reinforcement across the entire pier section, could result in an abrupt and catastrophic failure of the foundation.

One item of mitigation was applied – the full -tension side of the line, going to the south-southeast, had its design tension load reduced by 6.7% (approximately 1,000-lbs per subphase, or 9,000-lbs total for all phase wires attached at the design line loading condition. Line clearances were checked for the line section impacted and no significant issues were identified.

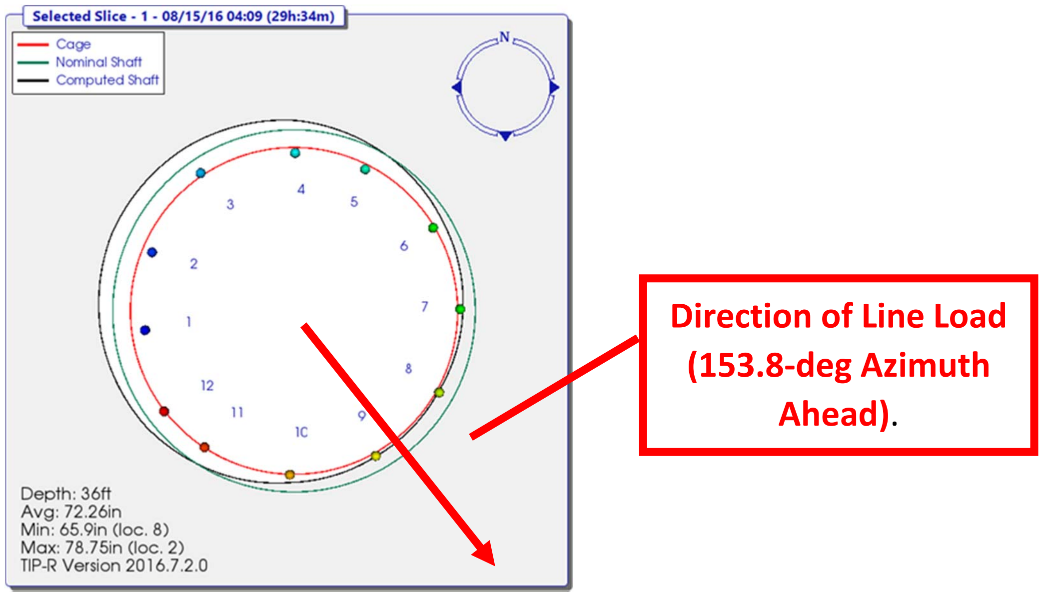

Figure 9 – Cross-Section of Shaft 1 at 36-ft Depth

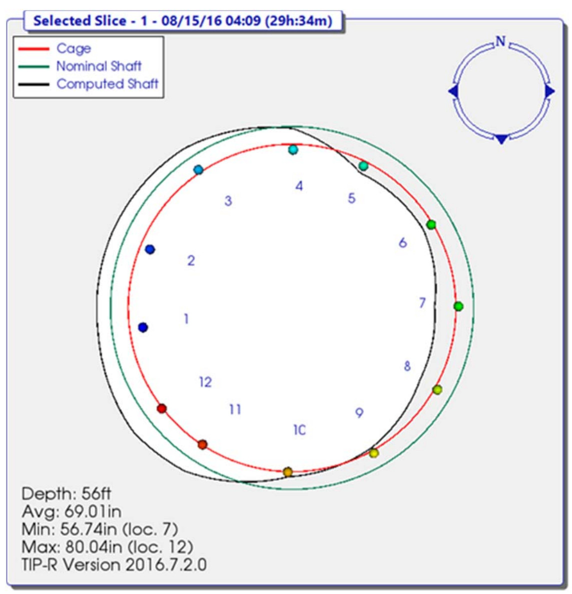

Figure 10 – Cross-Section of Shaft 1 at 56-ft Depth (Bottom of Pier)

Additional Testing Comments: This shaft was the first shaft analyzed for the project. As the project progressed, it was understood that a corrugated metal pipe (CMP) casing was permanently grouted into place, which normally took place the day before the shaft was placed. This heat contribution was initially attributed to the concrete placed for the shaft, thus incorrectly allocating placed concrete volume within the CMP cased section. Upon review a revised analysis was performed, with a correction in the boundary conditions accounting for the heat contribution from the grout, shown in Figure 11. The effective radius results were decreased near the shaft top, which allowed for an increase in effective shaft radius in the lower portion of the shaft. The portion of the shaft initially shown with zero cover had approximately two inches of cover. There was some slight improvement to the localized reduction at the bottom of the shaft, but the issue still remained.

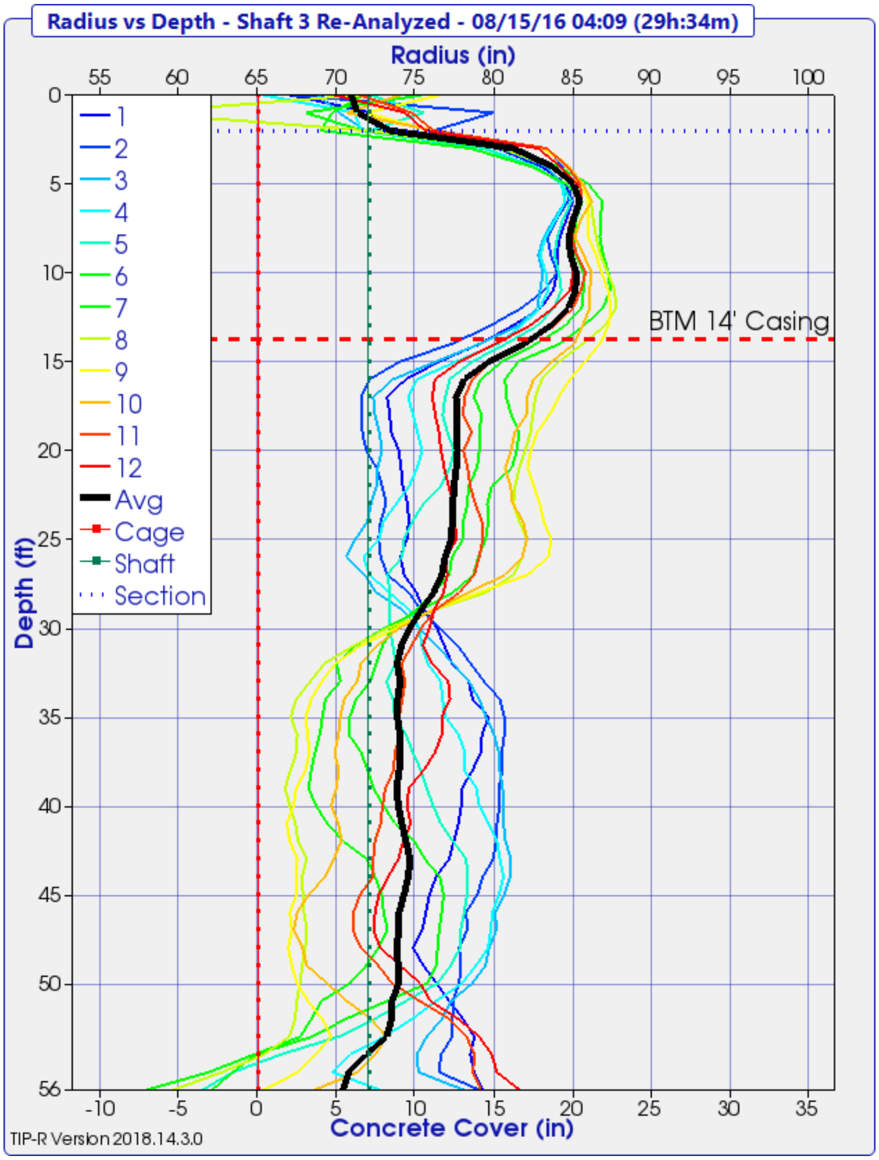

Fig. 11– Shaft 3 Revised Effective Radius versus Depth

Owner's Engineer's Follow-Up Comments:

With the re-evaluated and improved TIP analysis, it was determined that though concrete cover still did not meet the specified and ACI-318 requirements, there was expected to be sufficient cover to effectively encase the outer reinforcement and concerns about abrupt shear failure were abated. Though there was still an apparent inclusion in the bottom of the installed pier, by reducing the higher tension line loads as described previously the effective reduced embedment for the as-installed pier was then found to be acceptable. The re-evaluated pier was then found to have a sufficient factor of safety in terms of lateral capacity versus applied load and also met the specified serviceability requirements. As one final conditional check, the foundation contractor was to have the pier top regularly monitored for any unexpected displacement issues that may indicate insufficient pier performance during the contract warranty period.

SUMMARY

TIP testing is a valuable means of assessing the integrity of drilled foundations, and provides information that was previously unavailable by commonly used testing methods, particularly on the reinforcing cage alignment and concrete cover. The results indicate that even a shaft deemed "perfect" by other testing methods have some variations in effective radius, cover, alignment. A thorough understanding of the results can allow for detailed evaluation when the results are imperfect.

Though there were challenges in a few of the installations of the foundations for the subject project, by utilizing detailed field inspection reports and with the extensive use of TIP testing, the owner achieved a high degree of confidence in the foundation contractor's work plan and installations. Using tools like TIP advances the overall confidence of these types of installations and can only help the contractor's demonstration of their construction methods when employed properly.