DRILLED SHAFT BASE QUALITY REDUCTIONS IDENTIFIED WITH THERMAL INTEGRITY PROFILING

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Drilled shafts are a popular choice for deep foundations as they can support high axial and lateral loads, and they can be installed with limited disturbance to the surrounding area. Since visual inspection of the completed drilled shaft is not possible, non-destructive test (NDT) methods are commonly specified. Thermal Integrity Profiling (TIP) is a state-of-practice NDT method used for integrity and quality evaluation of drilled shafts, augered cast in place piles, diaphragm walls, and other concrete foundations.

Thermal Integrity Profiling utilizes heat generated during the concrete curing process to evaluate drilled shaft integrity. The collected temperature data is combined with installation details to generate an effective radius plot and 3D model. This method can be advantageous to both the contractor and owner based on the ease of installation of the instrumented cables, remote data collection, and reduced time between testing and reporting. TIP results and output models are dependent on proper selection of input parameters to normalize heat dissipation at the shaft ends. There is a perception that TIP cannot thoroughly evaluate the base of a shaft. However, with proper understanding and application of shaft bottom analysis, the full length of a deep foundation element can be effectively evaluated.

This paper includes case histories from Department of Transportation projects in the Midwestern United States where TIP was used to evaluate drilled shaft integrity. Analysis and interpretation of the data will be presented, and focus will be placed on the bottom of shaft adjustment parameters and resulting effective radius model. Data from uniform shafts without integrity issues versus shafts with cored and confirmed anomalies at the base are compared.

INTRODUCTION

Drilled shafts are a common deep foundation option, as they can support high axial and lateral loads, and they can be installed with limited disturbance to the surrounding area. Installation involves the drilling, stabilization, and clean-out of an excavation, setting of the reinforcing cage, and placement of concrete. Stabilization of the excavation is often achieved with permanent or temporary casings, the use of drilling slurry, or a combination of both. Each site presents unique challenges for installing drilled shafts due to varying stratigraphy, ground water conditions, slurry management, casing management, and design parameters including the concrete strength and workability, reinforcing cage geometry and clear space between the longitudinal members. Ensuring that the method of drilled shaft installation is compatible with the subsurface conditions is critical, as the shaft performance and reliability is sensitive to the construction techniques and methods used during installation.

Prior to concrete placement, shafts designed for end bearing or with an end bearing component require the cleanout of debris that may have settled or sloughed into the shaft base. Project specifications often set limits for the allowable debris thickness that must be satisfied prior to commencing the concrete placement process. Quality assurance methods allow for either visual inspection, via camera of the shaft base with a Shaft Inspection Device (Mini-SID), or direct measurements of the debris thickness with the

Shaft Quantitative Inspection Device (SQUID). Additional quality assurance methods are available for determining the shaft verticality and profile with depth prior to concrete placement. Since visual inspection of the completed drilled shaft is not possible, non-destructive test (NDT) methods are commonly specified. Thermal Integrity Profiling (TIP) is a state-of-practice NDT method used for integrity and quality evaluation of drilled shafts, augered cast in place piles, diaphragm walls, and other concrete foundations.

Thermal Integrity Profiling utilizes heat generated during the concrete curing process to evaluate quality. Instrumented cables containing digital temperature sensors spaced every 1 foot (.3 m) are secured along the full length of the reinforcing cage. The cables are installed in accordance with ASTM D7949, which requires that they are installed equidistantly around the reinforcing cage with a quantity of one cable per 1 foot (.3m) of shaft diameter. Either during, or soon after the concrete placement process is complete, each cable is connected to a data logger that records the temperature versus depth in 15-minute intervals. The data is transmitted remotely to a cloud-based network where the TIP Engineer can monitor and download for analysis. The collected temperature data is combined with installation details to generate an effective radius plot and 3D model.

This method can be advantageous to both the contractor and owner based on the ease of installation of the instrumented cables, remote data collection, and reduced time between testing and reporting. Previous research projects have stated a perceived weakness in the method regarding analysis of shaft toe conditions. TIP results and output models are highly dependent on proper selection of input parameters to normalize heat dissipation at the shaft ends. As the testing method has advanced, additional data has been obtained that supports the test method can effectively evaluate shaft toe conditions with proper application of the adjustment parameters.

EXPECTED THERMAL PROFILE

Temperature versus depth measurements are recorded at each local cable position, as a function time, with the objective of capturing data at or near peak temperature. The temperature versus depth plots for all cables, also known as the thermal profile, provide the basis for qualitatively assessing drilled shaft integrity. Assuming the boundary conditions surrounding the drilled shaft are uniform and the shaft geometry is constant with depth, as presented on the left side of Figure 1, the temperature distribution is expected to be vertical over the majority of thermal profile as presented on the right side of Figure 1. The exception is near the top and bottom of the shaft, where there is a distinct region of decreasing temperature (Mullins 2016).

The average temperature profile is generally a representation of the shaft shape, with the exception of the end conditions where the decreased temperature zone (i.e., temperature roll-off) is caused by environmental transitions (Mullins et al. 2020). At the interface between the bottom of shaft ("BOS") and substrate material, or between the concrete at the top of shaft ("TOS") and air, the change from energy producer to diffuser forms an inflection point in the temperature profile that closely aligns with that of a hyperbolic tangent approximation (Mullins 2010; Johnson 2015; Johnson 2016). The observed temperature reductions at the end conditions must be adjusted and normalized prior to the generation of the effective shaft radius. The process for converting the normalized thermal profiles to effective radii is detailed by Belardo et al. 2021. A temperature to radius factor is established using the average concrete temperature at the time selected for analysis and the concrete volume placed over the installed shaft length.

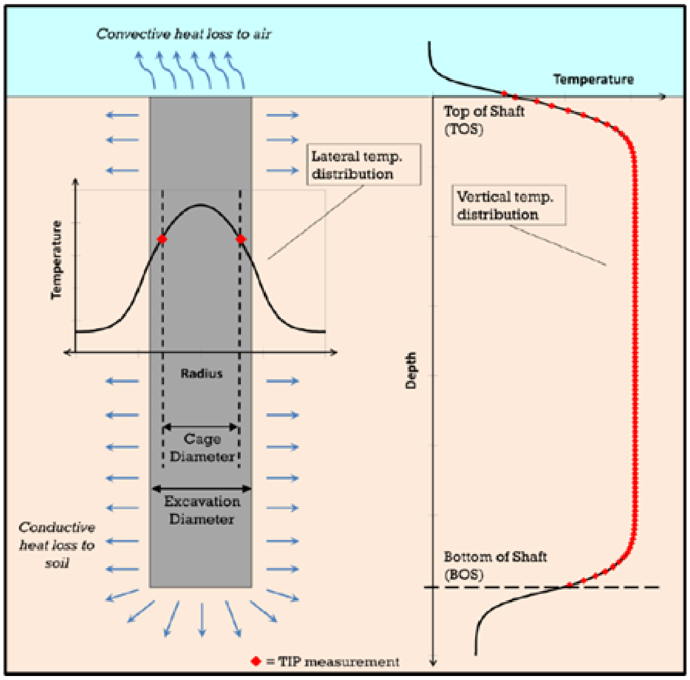

Fig. 1. Drilled Shaft Heat Dissipation and Resulting Theoretical Thermal Profile

(Adapted from Mullins 2016)

A hyperbolic tangent function is adjusted using four input parameters in the TIP-Reporter software. The parameters are adjusted to achieve a "best fit" of the adjustment hyperbolic approximation superimposed over the measured temperature roll-off at the shaft base. A similar approach is used to normalize the temperatures at the TOS; however, this paper focuses on the BOS adjustments. With the "best fit" signal matching approach to adjusting the hyperbolic, adjustments may be improperly applied either due to lack of experience or bias toward testing outcomes that can significantly affect the final TIP model. These parameters to normalize the BOS roll-off include:

- **Average BOS**; Normal internal shaft temperature above the influence of the temperature roll-off transition. Temperature should be selected from a region at least one shaft diameter above the base.
- **Soil Temperature**; Represents the lower bound on the hyperbolic. Temperature of soil boundary beneath the drilled shaft. Soil temperatures vary by geographic location but correlate well with the average annual air temperature at the project location.
- **BOS Inflection Point**; Represents the location of the transition from energy producer to energy dissipater (soil/rock) and input as the total concreted shaft length.
- **Scale BOS (α)**; where $\alpha = c\sqrt{t}$ the coefficient c ranges from .3 to .5 and t is the elapsed time in hours from the completion of the concrete placement to the time selected for analysis. Scale BOS represents the time factor or slope of the hyperbolic curve.

EXAMPLE PROJECT 1

GRL was contracted to perform TIP testing on a DOT project in the Midwest. The project consisted of two Interstate Bridges over a local road and railway. Both bridges were supported by driven piles at the abutments and drilled shafts at two piers, with each pier consisting of four shafts. TIP testing was specified to assess the post-constructed integrity of all sixteen drilled shafts on the project.

The shafts were designed to be 48-inches (121.9cm) in diameter through the overburden with 42-inch (106.7cm) diameter rock sockets. The contractor installed the shafts by advancing and seating a 54-inch (137.2cm) temporary casing approximately 1-foot (.30m) into weathered rock. Subsurface conditions based on nearby borings indicate hard sandy clay loam and sandy loam with sand seams from the top of shaft to a depth of 7 feet (2.1m). This layer was underlain by fine to coarse sand to the top of weathered rock at a depth of 12.27 feet (3.7m). Groundwater was encountered at a depth of 11 feet (3.4m), in the sand layer just above the weathered rock. Below the temporary casing, a 42-inch (106.7cm) diameter rock socket approximately 10-feet (3.0m) in length was drilled. All drilled shafts were reportedly installed using the same construction techniques. Concrete was placed via pump truck to a full length tremie extending to the base of the shaft.

The thermal profile presented in Figure 2 is representative of the TIP data collected on this project. The data is shown for a shaft, designated Shaft 1, at peak temperature which corresponds to the time selected for analysis. A roll-off in temperature at the top of shaft transitions to higher-than-average temperatures in the region of the oversized 54-inch (137.2cm) temporary casing. The measured temperatures reduce where the shaft transitions to the 42-inch (106.7cm) diameter rock socket. The temperature profile is relatively consistent through the region of the rock-socket with a roll-off in temperature observed near the shaft base. Slight cage shifting is observed from a depth of 10 feet (3.0m) to the base of the shaft such that cable 2 is nearer the soil/rock interface and cable 4 is nearer the shaft center.

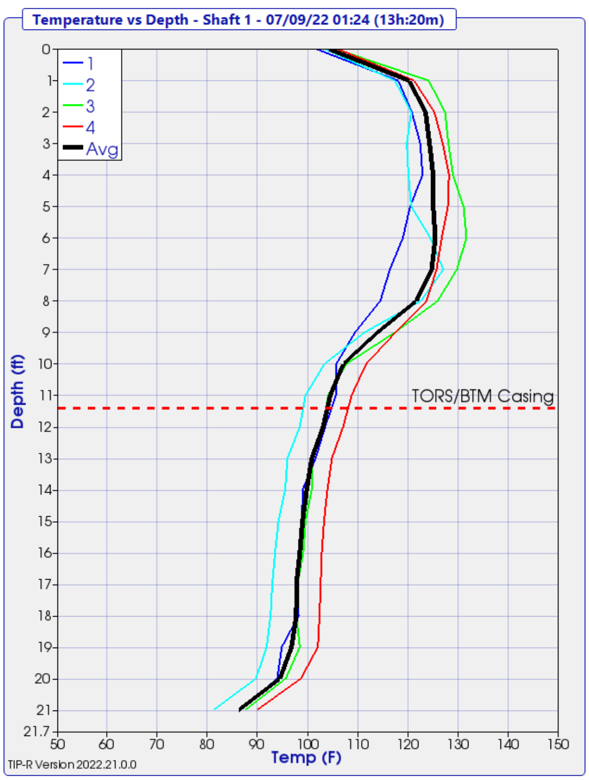

Fig. 2. Shaft 1: Temperatures versus Depth Graph at Peak Temperature

The overall concreted length of Shaft 1 was 21.7 feet (6.6m) and the bottom of cage was suspended approximately 6 inches (15.2cm) above the shaft base. The bottom sensor was affixed at the bottom of the reinforcing cage. Figure 3 presents the BOS adjustment applied to normalize the bottom roll-off in temperature. The red dashed line represents the expected heat loss based on the four input BOS adjustment variables. The red dashed line is superimposed over the average temperature measured near the base of Shaft 1. The upper bound on the hyperbolic is the average temperature above the roll-off influence (Avg BOS) which was selected at 97.9 °F (36.6 °C). The lower bound on the hyperbolic is input as the soil temperature which is 53°F (11.67 °C) in the project geographic region. The point of inflection (BOS) is input as the concreted shaft length which is 21.7 feet (6.6m). Increasing or decreasing the BOS shifts the entire hyperbolic curve up and down. Placement of the hyperbolic curve nearer the bottom of the collected data yields a stronger adjustment (greater increase in effective radius), whereas moving the hyperbolic below or away from the bottom sensor yields less of an adjustment. The analysis software does not allow the BOS to be input less than the shaft length to help prevent the masking of a soft toe. Lastly, the Scale BOS was calculated and input as 1.5 by multiplying the coefficient c of .4 by the square root of the elapsed time of 13.2 hours after placement.

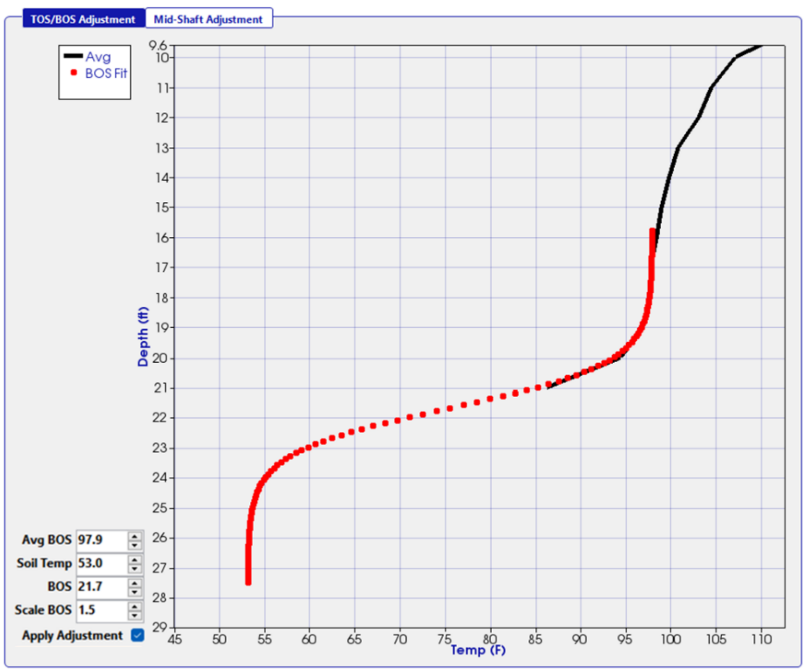

Fig. 3. Shaft 1: Bottom Roll-Off Adjustment

Results of the TIP analysis for Shaft 1 are presented in Figure 4. The left plot displays the Effective Radius vs. Depth, where the upper x-axis is the effective radius, and the bottom x-axis is estimated concrete cover. The reinforcing cage is represented by the vertical red dashed line. The green dashed line represents the nominal effective radii based on the reported casing and rock-socket diameters. The modeled effective average radius is consistent with the nominal shaft diameter and no anomalies are indicated. Note that after applying the BOS adjustment as detailed in Figure 3., the resulting shape is uniform near the bottom of the shaft. The right plot of Figure 4. presents a 3D representation of Shaft 1.

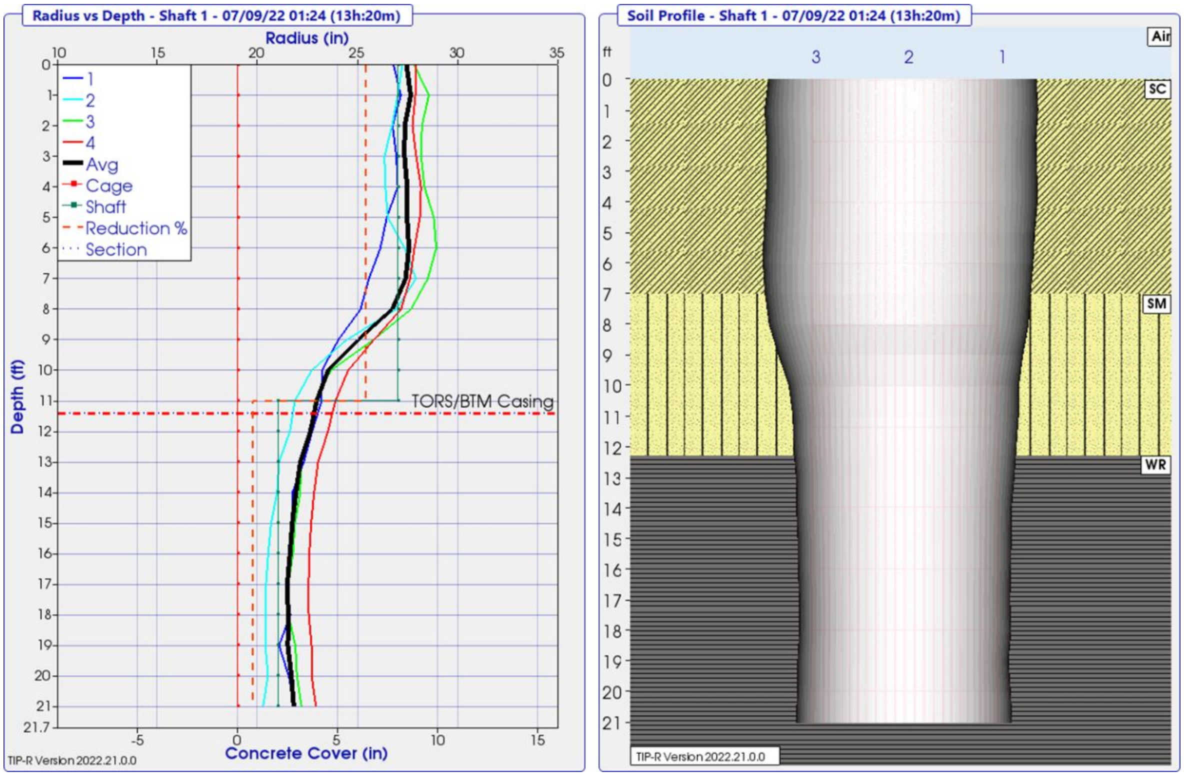

Fig. 4. Shaft 1: Effective Radius Graph (left) and 3D Presentation (right)

The general characteristics of the thermal profile for Shaft 2 are similar to Shaft 1, with exception to lower portion of the rock-socket. The Shaft 2 peak temperatures are presented in Figure 5. Unlike Shaft 1, the roll-off in temperature begins greater than one diameter up from the base of the shaft. Additionally, there is an observed inflection point in the collected data where the measured temperature transitions near a depth of 21 feet (6.4m).

Using the same methodology for applying the BOS adjustments for Shaft 2, presented in Figure 6., as were used in Shaft 1, it is apparent that the expected heat loss does not match the collected data. The primary difference in the BOS adjustment inputs is the BOS value which represents the concreted shaft length. Shaft 2 was installed to a depth of 22.3 feet (6.8m). After applying the BOS adjustment, the measured average temperature is well above the expected heat loss curve. In this case, even the most aggressive adjustment, with the curve at the bottom of the shaft, cannot significantly improve the reduction near the shaft bottom. An early roll-off is an indication of a potential soft toe condition.

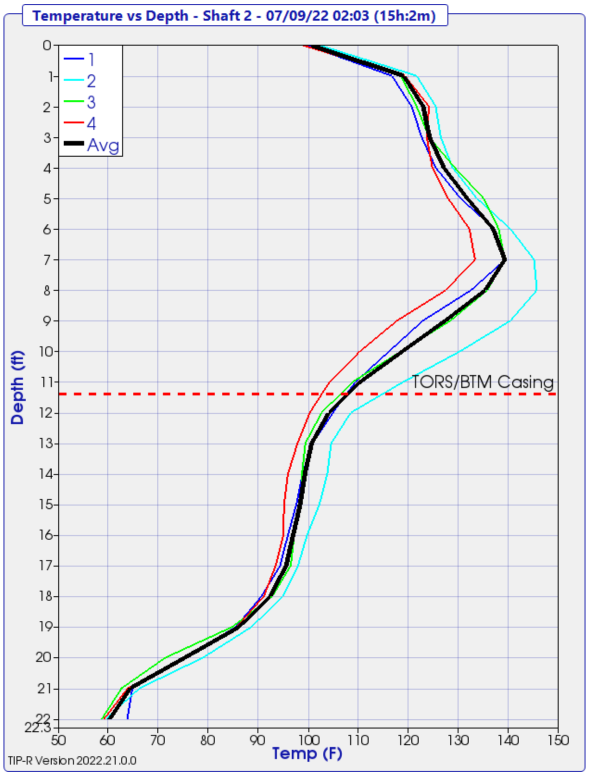

Fig. 5. Shaft 2: Temperatures vs. Depth Graph at Peak Temperature

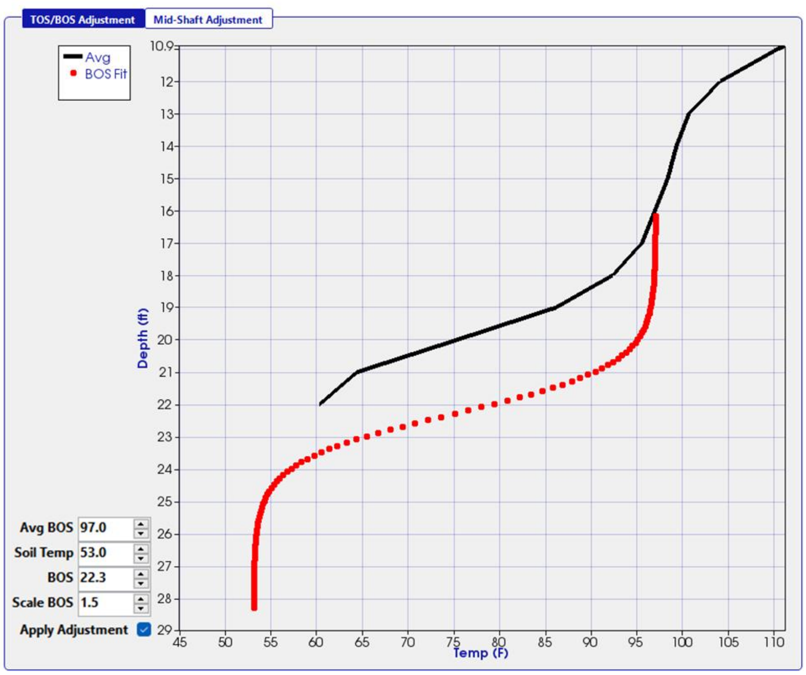

Fig. 6. Shaft 2: Bottom Roll-Off Adjustment

Figure 7 presents the results of the TIP analysis for Shaft 2. The modeled effective average radius is consistent with the nominal shaft diameter to a depth of 18-feet (5.49m). Below that depth, the effective radius reduces significantly, and is modeled as less than the cage radius for the lower 3-feet (.91m) of the shaft. Since all cables indicate a reduction, this may be an indication of a cross-sectional quality reduction. The 3D representation of Shaft 2 shows the exposed cage near the bottom of the shaft.

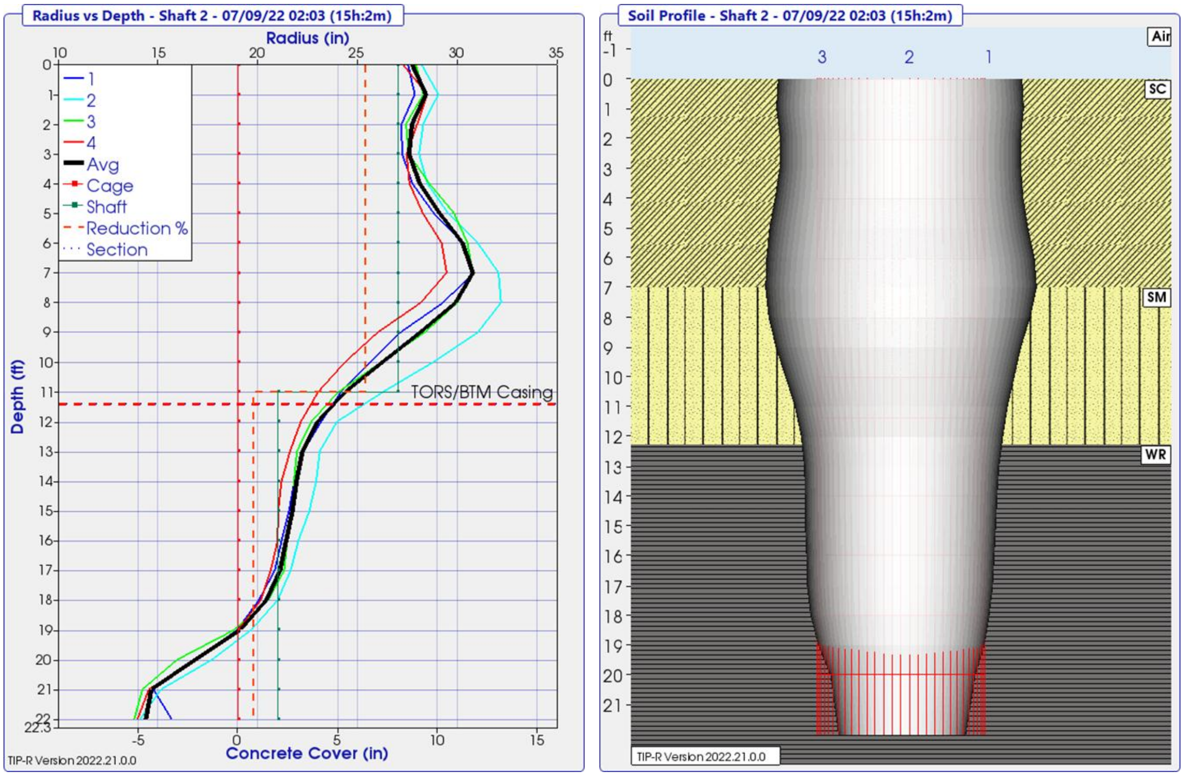

Fig. 7. Shaft 2: Effective Radius Graph (left) and 3D Presentation (right)

Examination of the temperature generated over time is another means of qualitatively assessing selected depth increments of a shaft. A comparison of the temperature generation from the bottom-most node from both shafts is shown in Figure 8. Minimal temperature generation is observed in Shaft 2 as compared to Shaft 1 which may be an indication of reduced cement content

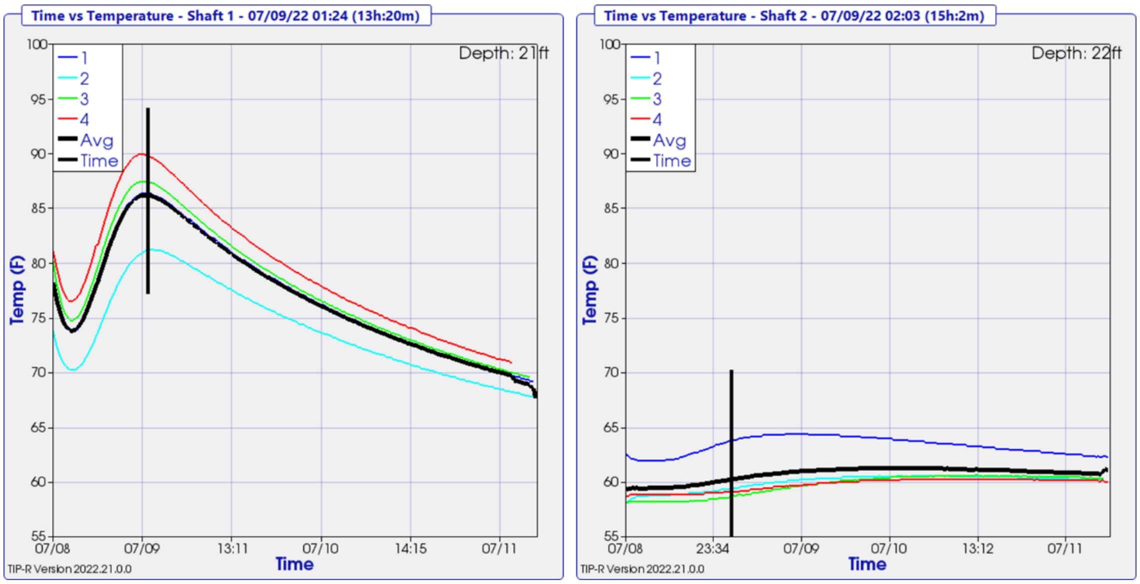

Fig. 8. Temperature vs. Time Graph for Bottom Sensors - Shaft 1 (left) and Shaft 2 (right)

Based upon the results of TIP testing, further investigation was recommended. Exploratory coring of Shaft 2 was performed. Figure 9 shows the core rig positioned to drill approximately 6-inches (15.2cm) inside the rebar cage at the shaft top and the extracted core results at the bottom of the shaft. The core shows limited recovery and segregated concrete over the lower 2-feet (0.61m). The soft toe condition was verified, which initiated remediation efforts.

Fig. 9. Shaft 2 Coring Operation (left) and Retrieved Cores (right)

EXAMPLE PROJECT 2

GRL performed TIP testing on a local bridge project in the Midwest. The bridge is supported on drilled shafts that consist of a 30-inch (76.2 cm) diameter upper temporary casing that extending to a depth approximately 18-feet (5.49 m). Below the temporary casing, a 24-inch (60.96cm) diameter rock socket extended approximately 9-feet (2.74 meter) into rock. Subsurface conditions indicate layers of dense sand and silt, and hard clay, overlying shale bedrock. Groundwater was encountered slightly above the weathered rock. Concrete was placed via pump truck to a full length tremie extending to the base of the shaft. Three TIP cables were installed along the full length of the 18 inch (45.7cm) reinforcing cage.

The basis of generating the effective average radius vs. depth as part of the TIP analysis is a relationship between average temperature and placed concrete volume. There is some inaccuracy inherent to estimating placed volumes due to waste for samples, pump truck priming, overpour, etc., as well as estimation of partial truck volumes. Most drilled shafts have theoretical concrete volumes that require multiple trucks; thus the errors are a smaller percentage of the total volume. With shafts that require less than one full truck of concrete, the estimation and consequent error can be significant. For this project, the theoretical placed volume of the shafts was less than 4 cubic yards and the reported volumes were on the order of 7 cubic yards. The shaft radius modeled was well oversized, even with a conservative reduction in placed volume.

Figure 10 shows the Temperatures vs. Depth for Shaft 3, with a profile as expected, and Shaft 4, with indications of a soft bottom. Similar to Example Project 1, the bottom of shaft temperatures for Shaft 4 contain an inflection point in the bottom roll-off and the temperature roll-off begins well above the expected values.

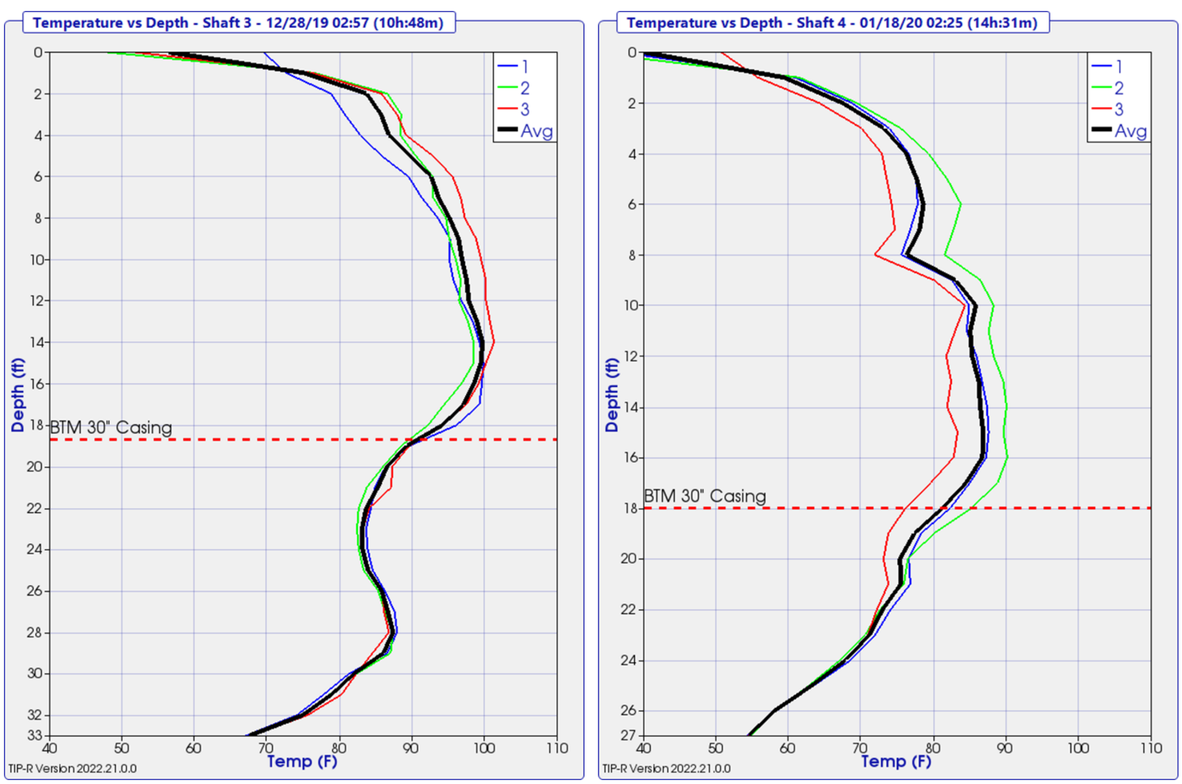

Fig. 10. Shaft 3 and 4 Temperatures versus Depth Graphs

The effective radius of Shaft 2 is presented in Figure 11 (right). When modeled based on the theoretical volume, the TIP model indicates an effective radius greater than the cage radius at the shaft bottom. However, the sharp linear reduction in effective radius is cause for further investigation. Since all cables indicate a drop in temperature, this may be an indication of a cross-sectional reduction in quality near the shaft base.

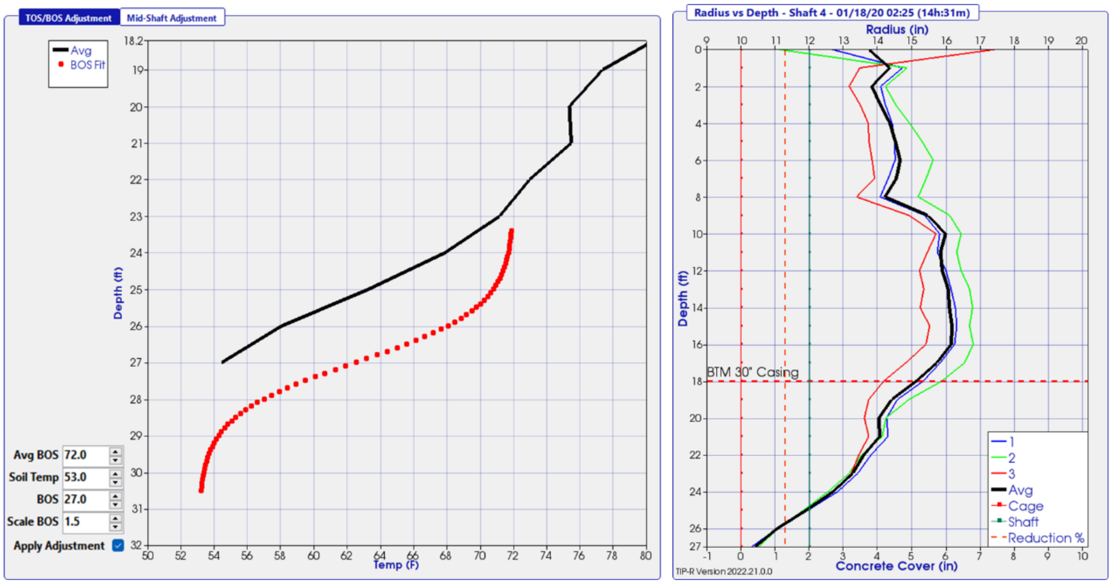

Fig. 11. Shaft 4: Bottom Roll-Off Adjustment (left) and Effective Radius vs. Depth (right)

A comparison of the temperature generation from the bottom-most nodes from each shaft is shown in Figure 12. Minimal temperature generation is observed in Shaft 4 as compared to Shaft 3. The limited temperature generation was interpreted as a region of lower cementitious content.

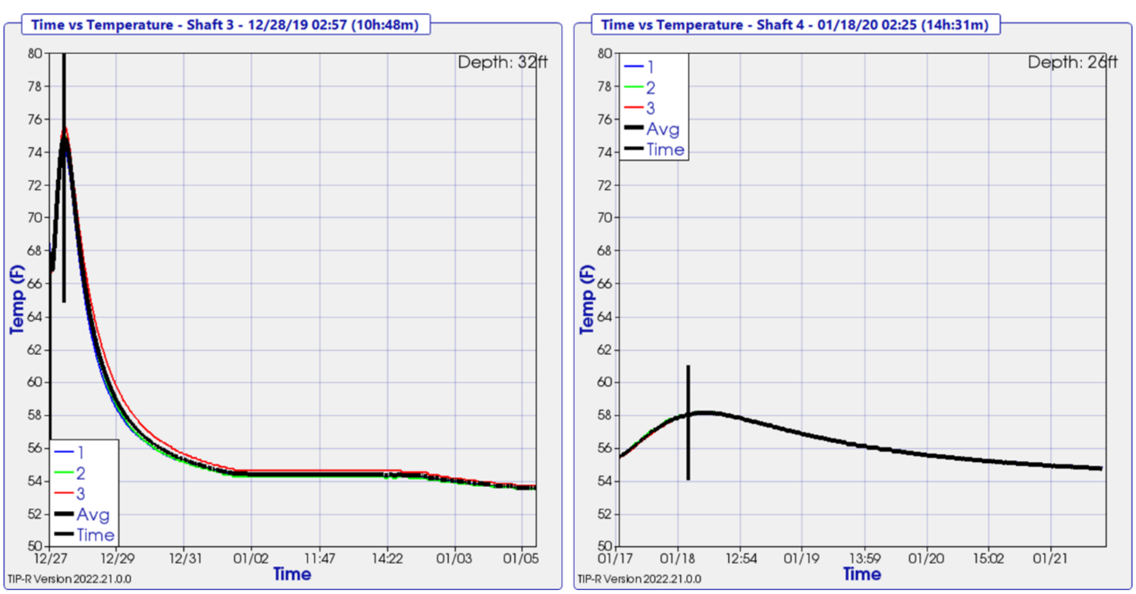

Fig. 12. Temperature vs. Time Graph for Bottom Sensors - Shaft 3 (left) and Shaft 4 (right)

Based on both the effective radius model and the temperature generated at the shaft bottom, further investigation was recommended. Coring operations and cores are shown in Figure 13. The attached section of rebar indicates the length of core without retrieval.

Fig. 13. Shaft 4 Coring Operation (left) and Retrieved Cores (right)

CONCLUSIONS

Thermal Integrity Profiling is a state-of-practice NDT method used for integrity and quality evaluation of drilled shafts, augered cast in place piles, diaphragm walls, and other concrete foundations. The observed temperature reductions at the end conditions of the thermal profile must be adjusted and normalized prior to the generation of the effective shaft radius. The procedure for normalizing the temperature roll-off at the bottom of a shaft consists of a signal matching approach using four parameters: average bottom of shaft temperature, soil temperature, bottom of shaft inflection point, and scale BOS. A thorough understanding of the application of these parameters is required to effectively assess the bottom of shaft integrity.

In addition to viewing the Temperature vs. Depth plot at the time selected for analysis, the Time vs. Temperature graph allows for additional qualitative assessment. Viewing the Time vs. Temperature data is especially useful when comparing "normal" or "expected" temperature data versus regions of integrity concern. The methods and case studies from DOT projects presented in this paper demonstrate how TIP testing and analysis can thoroughly evaluate shaft bottom conditions. Further studies of temperature generation over time at the bottom of drilled foundations with confirmed integrity issues may advance analytical tools and assessment methods.

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