INTERPRETATION AND EVALUATION OF THERMAL INTEGRITY PROFILING MEASUREMENTS

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ABSTRACT

Thermal Integrity Profiling (TIP) is a non-destructive method used to evaluate drilled deep foundation integrity. This integrity testing method is specified more frequently, and is becoming an industry standard in the transportation and private construction sectors. This testing method utilizes heat generated during the concrete/grout curing process to assess deep foundation integrity over the evaluated length. With compilation of the measured temperature versus time and installation records, a model of the Effective Average Radius versus measurement depth is generated. The generated effective shaft model is highly dependent on specific construction details, subjective modeling parameters, and proper interpretation of concrete/soil heat dissipation characteristics.

Key components of the TIP analysis include both qualitative and quantitative assessments. Qualitatively, variations or sharp reductions in temperature profiles may indicate potential anomalous regions. Quantitatively, a correlation is established between measured temperatures and estimated Effective Radii for subsequent integrity evaluation. Best practices in processing the TIP measurements are presented, including selecting the optimal time for analysis, normalizing the thermal profile, and proper interpretation of potential anomalous regions. Recommendations for implementing mitigation efforts and interpretation of the TIP results are presented.

Keywords: Thermal Integrity Profiling, TIP, drilled deep foundations

INTRODUCTION

Thermal Integrity Profiling ("TIP") is a non-destructive quality assurance method for evaluating post-concreted drilled deep foundation integrity and geometry. The general procedure involves measuring the temperature profile within the drilled foundation element during the concrete curing process (ASTM 2014). As concrete cures, heat is generated as a result of the exothermic chemical reaction between cementitious materials and water. Combined with a characteristic model of heat diffusion to media surrounding the curing concrete (e.g., soil, water, or air), relative changes along the temperature profile can indicate potential differences in the foundation quality. These differences can manifest as reduced concrete quality, foundation geometric changes (either anomalous regions or known geometric transitions), and/or large environmental changes.

Drilled deep foundations are becoming increasingly more common due to high loading capacities, accommodation for construction in difficult subsurface conditions or very dense soil, and relatively low induced noise and vibrations. A variety of drilled foundation construction techniques exist, and often a particular quality assurance method can be limited in its application or the degree to which the foundation integrity can be assessed. Additionally, construction practice encompasses a wide range of variables, such as the concrete mix design, proper implementation of the construction methods, as well as local considerations and expertise (e.g., optimizing practice relating to regional subsurface strata and climate). TIP is advantageous as it provides means to evaluate the entire cross-section of the foundation, and along its entire instrumented length. TIP therefore overcomes limitations from alternative integrity testing methods of assessing the concrete cover in addition to the shaft core, as well as implementation in small diameter augered cast-in-place ("ACIP") piles to large diameter drilled shafts (Piscsalko et al. 2015). Heat generation mechanisms during the hydration process are directly related to the concrete mix design, particularly the chemical composition of cementitious materials, TIP permits evaluation of variability in the concrete mix placed along the foundation length (Mullins 2010). Above all, real time data acquisition and integrity evaluation during the curing process allows for rapid assessment of TIP measurements.

Primary methods for measuring the temperature profile in a drilled deep foundation consist of advancing an infrared temperature probe in pre-installed access ducts (ASTM D7949 Method A) or embedding thermal sensors installed on vertical steel reinforcing elements (ASTM D7949 Method B). Embedded thermal sensors yield temperature measurements obtained over time to generate a time-history of the heat generation process. Typically, data acquisition begins immediately before or just after concrete is placed, and continues until the peak temperature has been achieved. Evaluation of TIP measurements is often performed for the peak temperature profile; however, critical insight into shaft integrity can be obtained prior to peak temperature, even within hours after concrete placement. This allows for early detection of potential anomalous regions. This can be crucial, for example, where multiple piles are installed in a single day, providing insights into shaft integrity and whether foundation installation methods are compatible with particular site conditions.

Significant benefits in detecting construction defects are realized using embedded thermal sensors (Boekmann and Loehr, 2018). Therefore, focus will be placed on evaluation of TIP measurements using these sensors. The embedded sensors (defined as nodes) are Thermal Wire® cables, and consist of an electrical cable with digital thermal sensors spaced every 30-cm (1-ft). These wires are directly attached to the longitudinal steel reinforcing bars, typically one wire per 30-cm (1-ft) shaft diameter. Data acquisition units are connected to each embedded wire and data is generally sampled in 15-minute intervals for each node until peak temperature is reached. Remote data acquisition technology can be implemented for real-time data evaluation through a cloud-based network. Most shafts reach peak temperature within 24 to 48 hours after placement. Although, cases have been documented where peak temperature has been achieved in as early as 6 hours after placement on small diameter piles (e.g., 30-cm diameter) to as high as 72 hours after placement on large diameter shafts (e.g., > 3-meter diameter). The time to peak temperature is also highly sensitive to the mix design selected and use of admixtures.

TIP measurement evaluation can be divided into qualitative and quantitative assessments. Qualitatively, the measured temperature profile at various elapsed times after concrete placement provides indications of the uniformity in concrete quality and shaft geometry over the instrumented foundation length. Quantitatively, the temperature measurements are correlated to an effective shaft geometry when integrated with the foundation installation records (e.g., concrete volume placed). Acceptance methods can then be applied to determine if the constructed foundation conforms to the intended design (Piscsalko et al. 2016). Each assessment requires an understanding of the underlying theory of TIP, proper application of data adjustment/normalization procedures, adequate construction records, and ultimately engineering justification in differentiating between various mechanisms of heat gain/loss or dissipation to the surrounding media. Critical assessment of these elements is discussed herein, and illustrated using lessons learned from case studies encompassing various drilled construction techniques over a wide range of site conditions.

UNDERLYING THEORY OF TIP

The theoretical thermal profile from TIP provides a baseline for the expected thermal profile, and allows for a comparative analysis with collected thermal data. The thermal profile for a foundation element is a graph of the recorded temperatures versus depth/elevation at a selected time interval after placement. Fig. 1 illustrates how the heat of hydration generated from the curing cement dissipates to the surrounding environment. The rate of temperature rise is on the order of eight times the rate at which the surrounding environment can dissipate the temperature after peak energy production (Mullins et. al 2020). The heat transfer along a majority of the shaft length is radial, with exceptions near end conditions where heat dissipates longitudinally to air above a shaft and to substrate material beneath it. Assuming boundary conditions are uniform with depth, the resulting theoretical thermal profile is represented by the red dashed line in Fig.1. Therefore, the vertical temperature distribution for a perfectly cylindrical shaft is uniform throughout the majority of its length. The exception is near the top and bottom of the shaft where there is a distinct region of decreasing temperature (Mullins 2016).

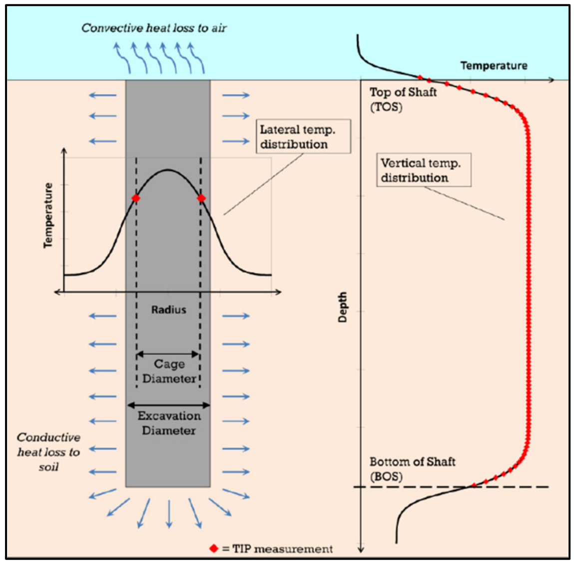

Fig. 1. Drilled Shaft Heat Dissipation and Resulting Theoretical Thermal Profile (adapted from Mullins 2016)

When collected TIP data are compared against the theoretical profile, characteristics of the recorded thermal profile may indicate non-uniformities in shaft cross-section or quality. The temperature distribution across a shaft's diameter is bell-shaped, with the highest temperatures recorded near the center and the lowest temperatures recorded near the shaft/soil interface. Since the temperature measurements are sampled on the near-linear portion of the bell curve, generally where the cage is located, instances of the laterally shifting of the reinforcing cage with the respect to the drilled diameter are easily identified. Cage shifting is evidenced by higher-than-average temperatures observed where the cage has shifted towards the center of the shaft, and an equal decrease in temperature by the diametrically opposite cable location where the cage is nearer the shaft soil interface.

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). TOS and BOS roll-off adjustments are applied to normalize the thermal profile where temperature reductions are observed based on relative differences between measured and theoretical heat dissipation effects. The parameters used to adjust the BOS roll-off include an average BOS temperature, soil temperature, BOS inflection point, and scale BOS time factor (α). Parameters for adjusting the TOS roll-off include an average TOS temperature, inflection temperature, TOS inflection point, and scale TOS time factor (α) (Mullins et al. 2020).

Adjustments should also be performed to normalize the thermal profile along the length of the shaft where observed temperature changes are caused by changes in diffusivity at environmental transitions. Since environmental transitions can alter the thermal signature, adjustments to the thermal profile must be addressed to properly assess shaft integrity. Commonly observed environmental transitions include air to soil, air to water, and water to soil. Mid-shaft adjustments are applied at each boundary transition based on similar hyperbolic approximations used to account for the shaft end effects on the temperature profile.

The thermal profile is converted to an effective radius profile by deriving a temperature to radius (T-R) factor based on the average radius (R_{avg}) and average temperature (T_{avg}). The average radius is computed based on the reported volume placed over the shaft length.

$$R_{avg} = \sqrt{\frac{V}{\pi \ x \ L}} \qquad [1]$$

Where V = concrete volume placed, and L = concreted shaft length.

Units must be consistent, i.e., if V is measured in m^3, then L should be input as meters. The average temperature is based on the measured overall average temperature at the time increment selected for analysis. The local temperatures (i.e., measured at each node and along each Thermal Wire® cable) are then multiplied by the T-R factor to yield the Effective Radius profile. The term Effective Radius is generally defined as the radius of intact concrete that would produce the measured temperature (Mullins 2016). However, the Effective Radius encompasses both geometric and concrete quality variations along the shaft length. Therefore, the Effective Radius profile is better recognized as an adjusted model of the shaft incorporating both the measured temperature profile and shaft installation records. When considering the Effective Radii as a geometric parameter, local concrete cover (at a specific location) can be estimated from subtracting the nominal cage radius from the TIP computed Effective Local Radii.

QUALITATIVE ASSESSMENT OF FOUNDATION INTEGRITY

Qualitative examination of the temperature profile and time history of the heat generation can accommodate identification of potential non-uniformities along the instrumented foundation length. While applying acceptance criteria requires additional steps, temperature measurements can provide early detection of:

1. Improper installation of embedded sensors.
2. Relative increases or decreases in the temperature profile as a function of depth, often requiring further assessment.
3. Soft bottom condition.
4. Cage shifting.
5. Localized anomalous regions based on large variation in the measurements from individual wires at the same depth.
6. Environmental influences on the temperature profile, such as relative variation in the peak temperature versus the ambient air/soil temperature, and transitions from air to water and/or water to soil.
7. Differences in concrete mixes among truck placements due to temporal temperature variations versus depth.

Detecting anomalous zones in drilled shafts near the shaft head and base can prove difficult due to combined effects of potential anomalous zones and heat dissipation to the surrounding media. However, a misconception is that no information regarding foundation integrity within the roll-off zones can be obtained from TIP measurements. Figures 2 and 3 present common examples of temperature measurements within the TOS and BOS roll-off zones, respectively, for hypothetical uniform and flawed shafts. The dashed lines denote the theoretical (hyperbolic approximation) temperature roll-off for a uniform shaft. The normalized average temperature versus depth is shown on the top, while the normalized Effective Average Radii versus depth is shown on bottom (and will be discussed in the subsequent section). These examples may not apply to all foundation sizes, concrete mix designs, and geographic regions. However, the generalized cases may help the TIP consultant identify potential flaws within the roll-off zones. Specific comments related to each case are as follows:

Case I: Drilled shaft with uniform diameter and concrete quality over full embedment length. Measured temperature roll-offs at the shaft head and base are consistent with theoretical TOS and BOS roll-offs, respectively. A reasonable correlation would be for a 1.2-m-diameter shaft, 30 meters long, where roll-off zones extend approximately one diameter from the concrete to air/soil interfaces.

Case II: Similar to Case I, the shaft appears uniform over the instrumented length. However, the wires terminate above the bottom roll-off, and potential flaws may still exist where TIP measurements were not obtained. Proper planning is required to include an adequate length of instrumented wire in the testing program. Generally, at least one node should extend above the top of concrete (accounting for potential concrete placement above cutoff elevations), and the lowermost node should be as close to the shaft base as possible.

Case III: The TOS and BOS temperature roll-offs follow a linear decrease rather than the expected hyperbolic temperature reduction. Initial qualitative assessment may not identify any flaw, but additional TOS and BOS adjustments show relative reductions in these zones.

Case IV: Identifiable flaws are located in the roll-off zones. There are several temperature roll-offs exhibited near the top of the shaft (Fig. 2), despite construction records indicating a uniform shaft in this zone. The temperature at the bottom of the shaft (Fig. 3) never exceeds the average soil temperature. This lack of heat generation is a direct indication of significantly reduced, or the absence of, cementitious materials at the shaft base.

Fig. 4 presents four cases where environmental transitions exist along a cased section of the drilled shaft. Each case exhibits multiple temperature roll-offs at the transitions from concrete to air, air to soil or water, and/or water to soil. When a shaft transitions through these drastically different boundary conditions with depth, variations in the thermal profile are due to changes in diffusivity. These observed changes caused by boundary, not geometric changes, must be accurately identified to properly interpret the temperature profiles. Mid-shaft adjustments are applied to normalize these temperature profiles to yield relatively uniform shafts for Cases V and VI, shown as the normalized Effective Average Radius versus depth. TIP results with mid-shaft adjustments should be accompanied with a detailed description of the changes in boundary conditions.

Cases VII and VIII require closer examination of non-uniformities in the temperature profile. For Case VII, a known geometric transition exists at an L/D of six, where installation records indicated an oversized casing terminated at the top of a rock socket. Mid-shaft adjustments should therefore only be applied where temperature variations were measured along the environmental transitions, and not where there is a known geometric transition. For Case VIII, an abnormal temperature roll-off was measured near the water to soil transition. Special considerations in applying adjustments to this thermal profile must be made to avoid masking any effect of potentially reduced concrete quality. The dashed line superimposed over the thermal profile represents the mid-shaft adjustment that should be applied in this zone. Consequently, a reduction in the Effective Average Radius results from the difference between the theoretical hyperbolic temperature profile and the measured temperature profile.

When Case VIII TIP results are correlated to installation records, the Effective Radius reduction is located in the cased zone and is therefore characteristic of non-uniform concrete quality rather than a geometric anomaly. It is therefore imperative that proper construction records are relayed to the TIP consultant to identify the locations of any environmental transition, and to differentiate these between known geometric changes, as well as potential anomalous regions.

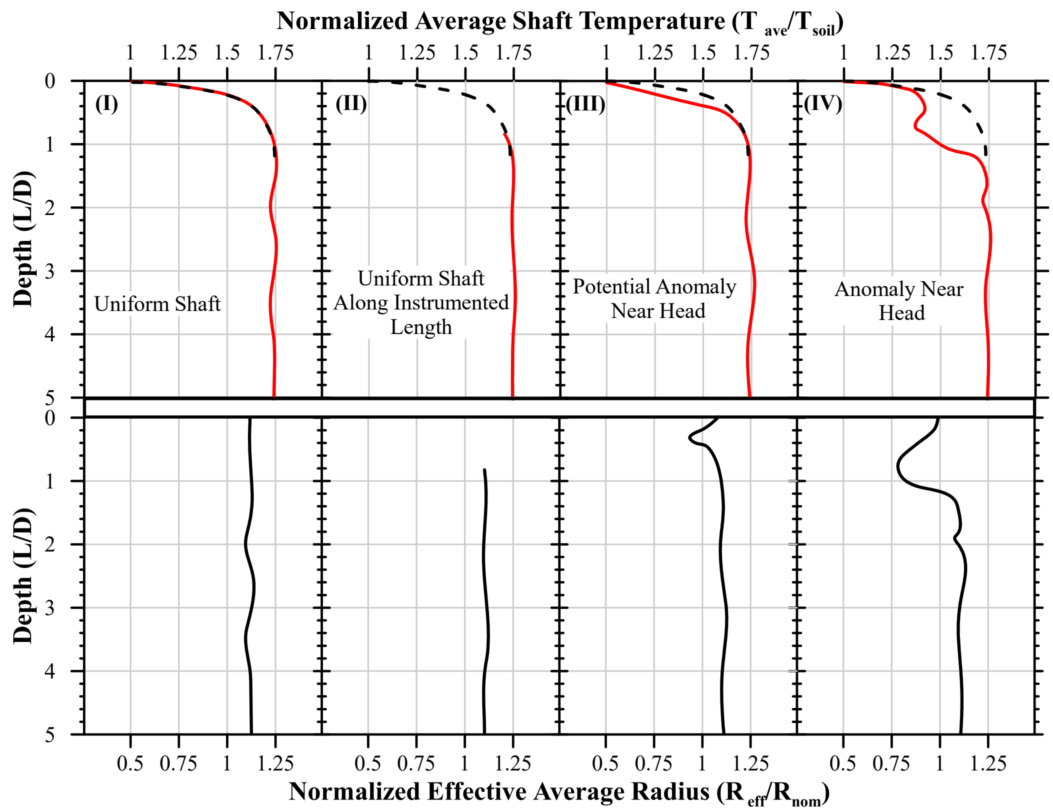

Fig. 2. Example TOS temperature roll-off in uniform and flawed drilled shafts.

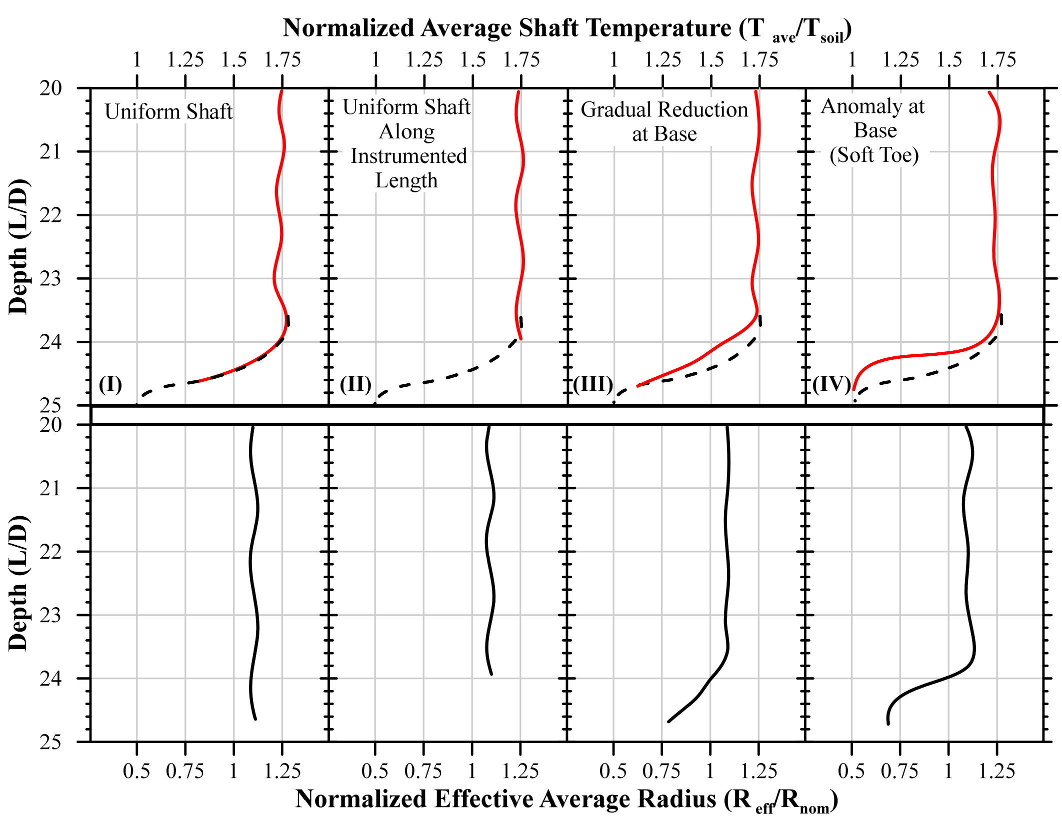

Fig. 3. Example BOS temperature roll-off in uniform and flawed drilled shafts.

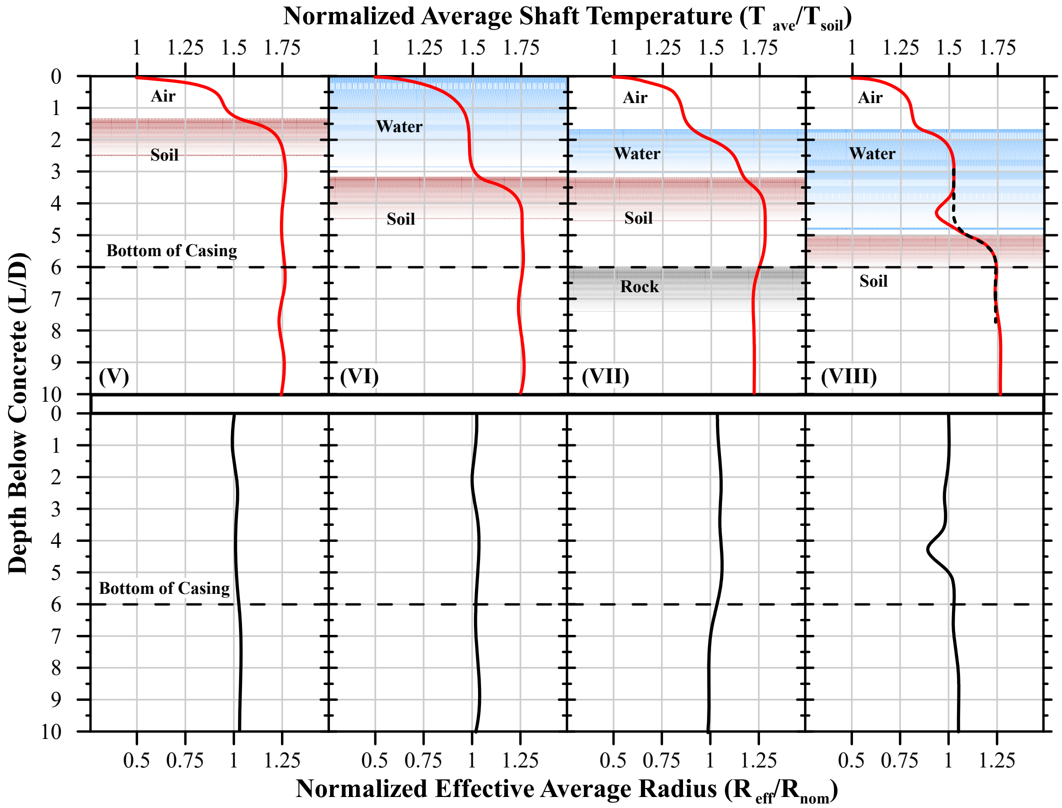

Fig. 4. Cased drilled shaft where mid-shaft adjustments are applied.

A basis for the thermal analysis is the use of a uniform concrete mix over the length of the shaft. Reported delays in the concrete placement process (e.g., pump truck breakdown, supplier delays, unplanned removal of tremie pipe), cold joints, inconsistencies in admixture or retardant dosing, water added onsite, and concrete batched from multiple suppliers can introduce non-uniformities in the thermal profile. Additionally, these factors may cause the temperature at various regions of the shaft to peak at different times and should be considered when selecting the thermal profile for analysis. A review of the time history allows a user to detect when the time to peak temperature varies with depth. In these cases, a modified thermal profile analysis, presenting the peak temperature at each 30-cm (1-ft) increment, independent of time, should be considered prior to proceeding with the analysis.

Refined qualitative assessment is often required for addressing more-complex anomalous zones. Issues during cage and concrete placement (e.g., off-center cage, cage deformation/bending, tremie pipe breach) can cause an anomalous zone that affects the shaft cross-section, and can also result in a relatively thin layer of reduced concrete quality. Multiple wire analyses and time-history evaluation of heat generation provide more effective means of identifying local anomalous regions. In contrast to Figures 2 through 4 where only the average temperature profile is displayed, Fig. 5 presents four representative cases where multiple wire analyses help identify anomalous zones. Specific comments related these cases are as follows:

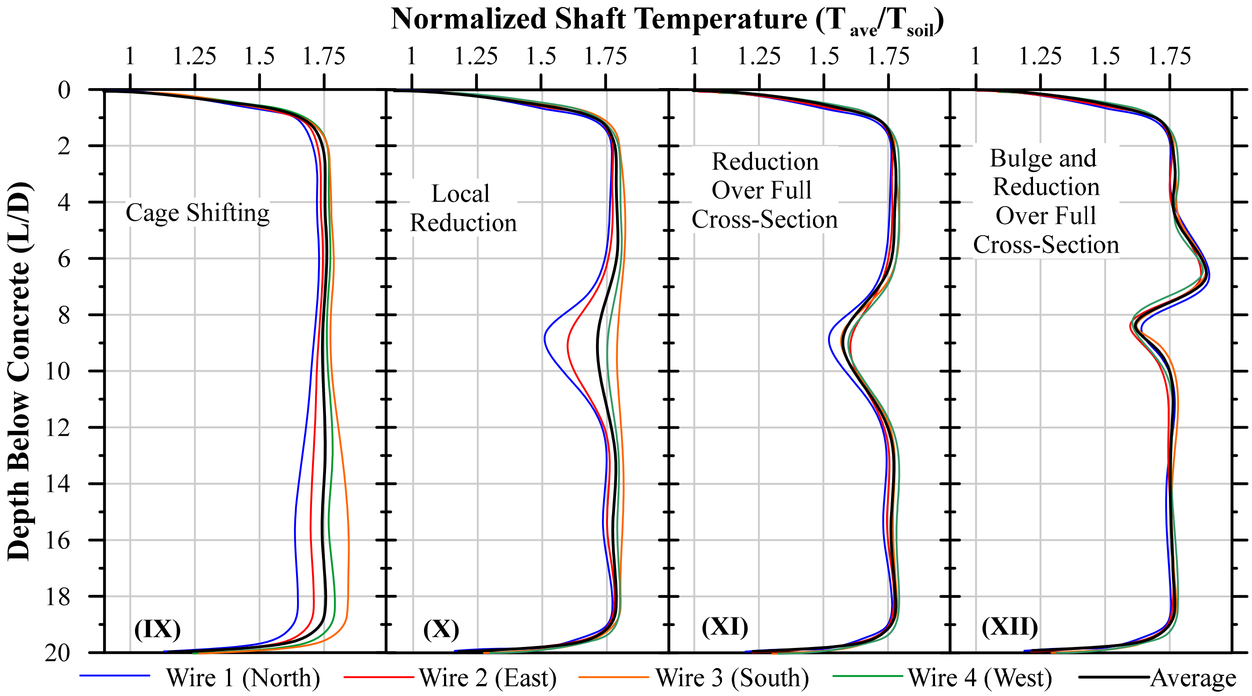

Fig. 5. Example cases of potential flaws identified from thermal profile.

Case IX: This is an example of cage shifting, where centralized cage alignment is evidenced near the drilled shaft head, but the cage becomes increasingly misaligned with depth. Inadequate centralizers, or lack thereof, and shaft diameter over-excavation are oftentimes the primary cause of cage shifting. Early identification from TIP measurements allows for implementing improved cage-alignment methods on subsequent foundation construction. An abrupt shift in alignment may be evident due to a change in drilling conditions, such as the transition from soil excavation (or cased zone) to a rock socket. The misalignment would therefore be between the soil and rock socket excavation, as opposed to sweeping or racking of the cage. Implementing multiple quality assurance methods, such as correlation to open shaft profiling devices, may help identify sources of misalignment.

Case X: Localized non-uniformities can be identified from relative temperature variations in each individual wire. Soil inclusions along the outside of the reinforcing cage may create localized flawed zones, as indicated by the reduction in temperature in Wires 1 and 2 (northeasterly direction) near an L/D of nine. However, evaluation based solely on the average temperature profile may result in Effective Radii within guidelines of radius reduction percentages, and thus may or may not meet the threshold for further evaluation. Observation of the temperature with time may show that the temperature difference at the area of concern is greater at ½ of peak temperature, and normalizing as the peak temperature is approached. When local reductions are observed, modeling the data prior to peak temperature may yield an improved estimate of the magnitude of the anomalous zone.

Case XI: At peak temperature, relative temperature variations measured in all wires at a specific depth is an indication of a flawed region encompassing the full cross-section. This may result from a breach of the tremie pipe, or concentrated from a particular concrete volume placed, and is a critical example of the value of qualitative analysis. As in Case X, evaluating similar datasets at timestamps earlier than peak temperature, in conjunction with the field information of a possible tremie pipe breach, delay in pumping, or truck placement records, can significantly improve the interpretation of TIP results.

Case XII: Increases in temperature may also be indicative of bulging or a larger quantity of cementitious material. When correlated to the subsurface stratigraphy, drilling records (e.g., torque records on continuous flight augers, visual observation of spoils removal), or concrete/grout volume records, differentiation between concrete quality and potential geometric non-uniformities can be achieved. The signature relative temperature increase over reduction is oftentimes characteristic of temporary casing removal in weak strata. For example, the casing tip was installed to an L/D of ten, and upon removal during the concreting process the soil collapsed, creating a compromised zone directly underneath. As the offsetting effects of bulge and neck will not show up on the concrete yield plots, installation records may not provide any evidence of this compromised zone, and if soil inclusion is located on the outside of the reinforcing cage, alternative integrity testing methods may not identify any flaw.

Due to inherent complexities of the complementing theories and effects of heat generation, dissipation to the surrounding environment, drilled deep foundation construction methodologies, the TIP consultant must rely on proper engineering justification, reinforced with installation observations to best distinguish between potential anomalous regions and known environmental or geometric transitions. There remain conditions where additional special considerations should be applied, such as climate sensitive implementation (e.g., cold weather conditions for small diameter foundations), which may require further research and extended duration of measurements to improve the temperature normalization to surrounding boundary conditions. Nevertheless, qualitative assessment of TIP data has proven to provide means of identifying areas requiring potential mitigation (i.e., construction/installation methodologies including casing removal procedures, source of concrete placed, tremie breaching, misalignment of cage or shaft/socket).

QUANTITATIVE ASSESSMENT OF FOUNDATION INTEGRITY

A quantitative TIP assessment involves the integration of the normalized thermal profile with the volume placed to develop the T-R factor and estimate the Effective Radius over the instrumented length. As previously stated, the Effective Radius encompasses both geometric and quality variations along the length of the shaft. Shaft installation procedures, field measurements, and conditions reported during excavation are incorporated in the development of the Effective Radii estimation.

TIP results may include a 3D graphical representation of the shaft and representation of the Effective Radii versus depth. These results can lead to a misinterpretation, where the reported Effective Radius is taken directly as the physical radius and the as-built shaft geometry. The presented Effective Radius encompasses both shaft cross-sectional area and concrete quality relative to the overall shaft temperature to Effective Radius relationship. Therefore, the presented Effective Radius may be shown as less than or greater than the reported diameter of a permanent casing, or inexact compared to the physical measurements taken near the shaft top. Reductions are modeled in the reporting software beginning at the shaft/soil interface and "moving" inwards toward the center. This approach encompasses shaft inclusions or necking which are generally observed as isolated temperature reductions from both a radial and vertical perspective. These reductions are often related to construction practices (e.g. removal of temporary casings without adequate concrete head to counter external pressures present at the casing tip).

In most cases, analysis of the thermal data is performed at or near the time of peak temperature. Thermal profiles from the peak or near peak are preferred to reduce the effect of external diffusion mechanisms while also allowing the temperature of all concrete to become more uniform, especially for extended concrete pours taking several hours (Mullins et al. 2020). Modeling prior to half-peak temperature is not recommended as a negative slope to the thermal profile is often observed. This increase in temperature with depth is age related and due to the placement process commencing at the base. At the time of approximately half-peak temperature, the upper and lower portions of the shaft normalize, resulting in a relatively uniform thermal profile. When temperature reductions are observed, and suspected to be Effective Radii reductions, modeling between half-peak temperature to peak temperature may yield improved results with respect to estimating the magnitude of the reduction.

With any output model, the reliability and accuracy are dependent on input parameters. The TIP model often falls under scrutiny when results deviate from permanent casing dimensions. When the TIP model indicates the Effective Average Radius is relatively uniform and also greater than the inside-radius of a permanent casing, the volume input to develop R_{avg} (Eq. 1) should be investigated. This over-estimation is generally the result of the input volume exceeding the theoretical volume. A practical, and sometimes conservative approach may be to reduce the volume until the Effective Average Radius yields a better correlation with the nominal casing diameter.

When isolation casings are used in conjunction with permanent casings, increases in temperature are often observed over the limits of this casing. The air gap between the permanent casing and the isolation is a poor thermal conductor which acts as an insulating boundary. This phenomenon may also occur, although to a lesser degree, when permanent casings are installed in dry soils. Increases in temperature may also be observed if the annulus around a permanent casing is filled with cementitious material prior to the shaft concrete placement, where grout temperatures are yielding elevated temperatures compared to soil temperatures. The annulus around a permanent casing may also be filled with concrete or cementitious material that spills over the top of casing during the pour. In either case, the extent of cementitious material placed in the annulus should be documented in relation to the top of the concreted foundation for proper adjustment to the thermal profile (i.e., using mid-shaft adjustments). If modeled without proper adjustments to the thermal profile, over estimation of the Effective Average Radius in the regions with elevated temperatures may result in under-estimation in other regions along the length of the shaft.

Existing acceptance criteria based on TIP results was presented by Piscsalko et al. (2016) as a Satisfactory (S) where Effective Average Radius reductions ranged from 0 to 6%, and local cover criteria met, and Anomaly (A) where Effective Average Radius reductions exceed 6%, or local where local cover criteria was not met. These classifications can reduce TIP results to a “pass” or “fail” solution, without consideration of the specific shaft loading requirements. Interpreting the results should be a collaborative effort between TIP consultant and drilling contractors to provide the Engineer of Record (EOR) the necessary information to determine acceptability based on specific loading requirements. Therefore, developing an anomaly matrix before the start of a project may expedite the remediation process and reduce potential project delays when integrity issues are detected.

Further Evaluation (FE) can been implemented in place of the Anomaly (A) categorization. When a shaft is deemed (FE), communication between the TIP consultant and project team is critical to determine a possible cause of the observed non-uniformity in TIP measurements. Cross checking critical input details may improve the results, such as the concreted length, volume placed, cage diameter, and distance from the bottom of instrumentation to the bottom of concrete.

DRILLED FOUNDATION MITIGATION

Following both qualitative and quantitative assessment of the TIP data, the TIP consultant generally provides recommendations on further investigation or evaluation based on the results. Even though the shaft concrete is being evaluated, integrity testing of foundations fall within the geotechnical, not structural, domain. It is important to acknowledge that the detailed structural evaluations and applied loads will not likely be available to the TIP consultant. Thus, the recommendations should be considered a guideline to be incorporated by the EOR.

The recommendations for investigation or evaluation are guided by the location of the anomalous zone. Issues identified near the shaft top should be visually inspected. Measurements of the shaft dimensions, exterior concrete strength, e.g., surficial cores, rebound hammer or Windsor Probe, or removal of soft, loose, or spalling concrete can allow for more detailed delineation of affected zones. Visual inspection or excavating to expose the anomalous zone is often the most straightforward and cost-efficient method to depths as limited by safe excavation or equipment limitations.

Recommending additional integrity testing, such as low strain integrity testing (PIT) can aid in evaluating the shaft integrity, particularly when upper portions of the shaft are in question. Depending on the shaft length and geometry, the test may be imprecise for evaluating questionable shaft toe conditions. PIT may be more ideally suited for anomalies located above the base of a shaft.

For anomalous zones identified below practical depths of visual inspection, the next step is evaluation of the results with respect to actual shaft loading conditions. If TIP results indicate a soft toe condition (see Cases III and IV in Fig. 3) then the shaft may be evaluated excluding the affected zone Coleman and Weaver (2019) provide a detailed structural analysis of shafts with zones of reduced effective area or reduced concrete cover.

If any of the previous actions do not provide viable solutions acceptable to the EOR then often the next step is advancing concrete core(s) to further delineate and sample compressive strength data in the questionable zones. There are limitations on the value of cores; the alignment of the cores relative to the shaft are often imprecise, as they are difficult to advance in close proximity to either the inside or the outside of the reinforcing cage. The value of the cores for evaluation is also reliant on the experience and quality of the exploratory drillers and coring equipment. With those limitations, a core can more definitively correlate reductions in effective radius with concrete quality. Bixler et al. (2015) and Coleman and Weaver (2019) present core results that correlate with TIP results with significant reductions in Effective Radius. When all cable locations indicate a reduction, this may be an indication of a cross-sectional reduction in quality and not solely a cover reduction. Winters and Mullins (2012) detail a drilled shaft with anomalous TIP results where the drilled shaft was exposed and revealed no change cross-sectional area. Coring revealed a quality reduction as confirmed by compressive strength tests. In cases where coring is impractical or the core(s) are inconclusive, anomalous shafts are tested for load capacity, using either static or dynamic load testing methods.

Remediation of a confirmed anomalous zone often involves hydroblasting to remove contaminated or poor-quality concrete followed by pressure grouting. Data loggers can be connected to the existing thermal cables during the pressure grouting process to qualitatively assess the remediation efforts. The collected TIP data cannot model the remediation, but can provide an indication of the proximity or effectiveness of grouting of reductions or voids based on the relative increases in temperature. Grout flow into the voids created from the hydroblasting process should register as an increase in temperature where previously, a temperature reduction was observed during TIP testing performed after shaft placement.

UTILIZATION OF TIP RESULTS IN ENGINEERING APPLICATIONS

Drilled deep foundation geometry is directly related to its geotechnical load-bearing capacity and structural resistance, considering axial static soil resistance as well as flexural and lateral resistances. These relationships are demonstrated by Piscsalko et al. (2016), and are summarized as follows:

- Circumferential surface area (geotechnical side-shear resistance); linearly proportional to radius.
- Cross-sectional area (axial compression/ tension structural resistance, and geotechnical end-bearing resistance); proportional to the square of radius.
- Moment of inertia (flexural resistance); proportional to the radius raised to the fourth power.

Where TIP results indicate a uniform shaft, Effective Radii incorporating known placed concrete volume accommodates review of geotechnical and structural resistances if needed. For example, enlarged surficial and base area will yield higher geotechnical resistance than initially computed with nominal geometry. This however assumes relatively small variations in geometry will result in nearly equivalent unit side-shear and end-bearing resistances. Application of unit resistances to relatively small variations in geometry may be limited in location and effect, but may guide designers in post-construction assessments. However, there remains no direct way of distinguishing geometric and concrete quality non-uniformities directly from TIP results alone. Relative changes in concrete compressive strength do not have the same proportional effect on the structural response to load as changes in geometry. Therefore, material quality reductions may have more, or less, of an effect on structural response to load than changes in geometry, depending on the extent of reduction and intended foundation design. For example, flexural resistance is not comparatively proportional to yield stress as are variations in foundation geometry. Reductions in yield strength may have no observable influence on side-shear resistance if the reduction extent is not detrimental to the structural performance. Proper utilization of TIP results in engineering applications therefore requires engineering justification and assessment of installation records to determine potential sources of non-uniformities in the temperature profile.

Strain gages are often embedded within drilled foundations for assessing load distributions under load testing. Conversion of strain to internal force requires a known axial rigidity, which is the product of cross-sectional area and material quality (i.e., elastic modulus). Non-uniformities along a foundation length must be adequately considered for calculating the internal force and unit soil resistances from measured strain. Improved estimation of foundation rigidity at strain gage locations can be achieved with thermal measurements. Additionally, internal calibration of foundation rigidity (Komurka and Moghaddam 2020; Komurka and Robertson 2020) accommodates back-calculation of concrete elastic modulus, which can then be applied to regions where geometric variations are identified from TIP (e.g., enlarged sections in upper weaker soils compared to nominal diameter in denser soils). Geo-structural interaction under axial loading is therefore significantly improved when incorporating TIP in static load tests, particularly for reduced uncertainty in estimating foundation rigidity.

Dynamic load testing on drilled deep foundations provide a fast and cost-efficient means of evaluating load-bearing capacity. Signal matching analyses require input of the foundation's dimensions (incorporated in the foundation impedance) in order to differentiate between static/dynamic soil resistances and impedance variations along the foundation length. TIP results can be utilized to evaluate non-uniform impedance, either taken directly as the non-uniform geometry, or as the percent reduction in quality and/or geometry. This provides improved confidence in the signal matching model and therefore greater certainty in the computed static soil resistance.

SUMMARY AND CONCLUSIONS

Thermal Integrity Profiling provides an effective means to rapidly detect potential anomalies in as-constructed drilled deep foundations. While significant benefits are achieved over alternative integrity testing methods, engineering justification and correlation to foundation installation records improves implementing TIP results in a quality assurance program. A series of cases were presented to demonstrate proper practice in interpreting and evaluating TIP measurements for typical drilled deep foundations. These cases included identifying commonly encountered variations in the thermal profile resulting from both integrity issues and construction practices. Special considerations were addressed for qualitatively assessing thermal profiles, and applying quantitative examination for shaft categorization purposes. Depending on the magnitude and location of the observed reductions, remediation efforts were provided based on existing state of practice methods. Encompassing the underlying theory, qualitative and quantitative interpretation, and recommendations in proper practice, the following conclusions can be made:

1. A key element of TIP evaluation is recognizing relative temperature changes along a foundation length. Differentiation between construction records, known environmental transitions (changes in boundary conditions affecting heat dissipation), and potential anomalous regions allows a TIP consultant to identify concrete quality and geometric non-uniformities. Qualitative assessment of the thermal profile may commence within hours after concrete placement, expediting the quality assurance program and implementation of potential mitigation or quality control practices.

2. The embedded thermal wire method is the preferred TIP technique particularly for assessing localized temperature variations and examining the time-history of heat generation. Multiple wire analyses accommodate quality assurance of the cage alignment, variations in measured temperature between wires at a specific depth (providing means of estimating the proximity of anomalous zones), and potential causes of identified flaws.
3. Heat dissipation at the top and bottom of shaft boundary conditions can be approximated as a hyperbolic function. Adjusting the thermal profile to account for temperature roll-off is required for proper quality assessment of the concrete quality in these regions. Deviation between measured and theoretical temperature dissipation effects may indicate anomalous zones such as a soft bottom condition or poor concrete quality near the top of shaft.
4. Proper documentation of known environmental transitions, such as air to soil, air to water, and water to soil, allows for proper application of mid-shaft adjustments to normalize the thermal profile. This is of particular importance where transitions between construction methods are concurrent with changes in boundary conditions, such as a cased shaft through soil terminating at the top of a rock socket.
5. Quantitative assessment incorporates thermal measurements and construction records to develop a model of the concrete quality over the instrumented shaft length. Aforementioned TOS, BOS, and Mid-Shaft adjustments may be required, in addition to the nominal shaft geometry and concrete volume placed over the shaft length. This results in calculated Effective Radii versus depth, which is oftentimes misrepresented as solely a geometric model. However, coupled with proper engineering justification and installation records, differentiating between non-uniformities in geometry and concrete quality may be achieved. Implementing multiple quality assurance methods, such as open shaft excavation profiling techniques, provide more-effective means of characterizing potential flaws in the as-built foundation.
6. Shaft categorization determined from TIP results conventionally subdivides the foundation as Satisfactory or Anomaly based on fixed percent reductions in Effective Radii from the nominal shaft radius. Reductions in geometry versus concrete quality may manifest in more or less of a degree depending on the extent of reduction and intended foundation design. Due to the complex nature of quantifying non-uniformities from temperature measurements, as well as specifying potential causes of anomalous zones, a collaborative effort between the TIP consultant and drilled shaft contractor is recommended. "Further Evaluation" is recommended for categorizing non-uniform shafts rather than strictly stating the identified anomaly is a definitive detriment to the foundation serviceability.
7. Where flaws are identified and regions are isolated for further evaluation, additional quality control and mitigation techniques can be implemented. Where applicable, visual inspection, concrete coring, Windsor Probe, Schmidt Hammer, and PIT tests can aid in evaluating the extent of anomalous zones. Hydroblasting to remove poor-quality concrete followed by pressure grouting can be an effective remediation technique.

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