Thermal Integrity Profiler

SP&R Part II, 775 Project# RB13-013

September 2019

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Background

Assessing the structural integrity of bridge foundations is critical to ensuring the reliability of the foundations and superstructure, as well as the safety of the traveling public. However, nondestructive methods currently used in practice to determine the integrity of reinforced concrete drilled shaft foundations are limited by their inability to provide full coverage of the foundation cross-section, particularly in the vital region outside of the rebar cage. The concrete cover outside the rebar cage is critical because: (1) it provides the soil-structure interface over which stresses are transferred to the soil to develop the geotechnical resistance and geotechnical capacity, (2) it offers protective cover for the rebar cage, and (3) it is the region of the cross section that resists the maximum bending stresses.

Currently, the most widely used testing methods for quality assurance of drilled shafts are the cross-hole sonic logging (CSL) and gamma-gamma logging (GGL) methods. For example, the Iowa DOT requires CSL tests for all drilled shafts supporting bridges, light towers, and sign structures. However, the CSL method can only detect flaws located between pairs of source and receiver CSL pipes, and not in the critical concrete zone outside the rebar cage. CSL results are also adversely affected by de-bonding of the access pipes, which can increase travel time and thus falsely indicate shaft defects or low quality concrete. The nuclear GGL method can detect flaws outside the rebar cage, but only within a 3 to 4-inch radius around each access pipe. Therefore, neither CSL nor GGL tests enable assessment of the concrete quality over 100% of the cross-sectional areas of typical drilled shafts.

The relatively newer Thermal Integrity Profiling (TIP) method was developed to overcome these limitations, by employing measurements of the heat of hydration of curing concrete. The temperature measurements can be made using either sacrificial wires of thermal sensors cast into the foundation, or an infra-red thermal probe lowered into access pipes cast into the foundation. Several previous studies have demonstrated that the technique can detect internal flaws such as soil inclusions or voids, as well as bulging, necking, and loss of concrete cover outside the rebar cage. However, the studies did not assess the accuracy of the technique for indicating the specific location, size, and general shape of the flaws.

Evaluation Procedure

The original goal of this project was to install defects having known dimensions and locations in a single full-scale test shaft, and compare the accuracy of the CSL and TIP methods for detecting the specific locations, size, and general shape of the defects. The original scope was greatly expanded to include defect installation and TIP testing of five full-scale test shafts (Table 1), and TIP testing of one production shaft. After weighing the relative advantages of probe vs. wire TIP testing systems, the Iowa DOT purchased a TIP probe testing system and training from Pile Dynamics, Inc. (PDI).

Table 1: Prefabricated defects installed in five test shafts

Test shaft: Diameter × Length	**Upper Defects**	**Lower Defects**
1: 5′×85′		
2: 5′×77′		
3: 6′×91′		
4: 6′×97′ w/5.5′×11′ rock socket		
5: 6.5′×98′ w/6′×13′ rock socket		

The artificial defects were secured to the rebar cages of five O-cell test shafts at two different elevations per shaft, either inside or outside the cage depending on the particular test shaft and elevation. The defects shown in Table 1 consisted of three types: (1) low-strength concrete (600 psi 7-day strength) cast in the form of cylinders, curved shells, or rectangular blocks, (2) sealed 6 by 12-in. plastic cylinder molds filled with aggregate, sand and water corresponding to a concrete mix with cement omitted, and (3) clayey soil cuttings placed in woven polypropylene sandbags and compacted into rectangular shapes using a steel tamper. For Test Shafts 3 through 5, PDI also donated personnel, Thermal Wires®, and TIP dataloggers so that measurements could be made by both the TIP probe and TIP wire methods.

The cross sectional area of the defects ranged from 2.8% to approximately 10% of the gross shaft cross sectional area. The height of the defects was also varied between 1 and 3.5 ft, as the height and volume of defects relative to the shaft dimensions also affect their detectability. TIP probe tests were initiated 20 to 24 hours after the end of the concrete pour for each test shaft. For Shafts 3, 4 and 5, thermal wire data was also recorded at intervals ranging from 5 to 15 minutes, starting before the shaft pour and ending a few days afterwards. Figure 1 shows both the probe and thermal wire systems being used for TIP testing. A close-up of the temperature sensor and circuitry that comprise PDI's Thermal Wire® system is shown in Figure 2.

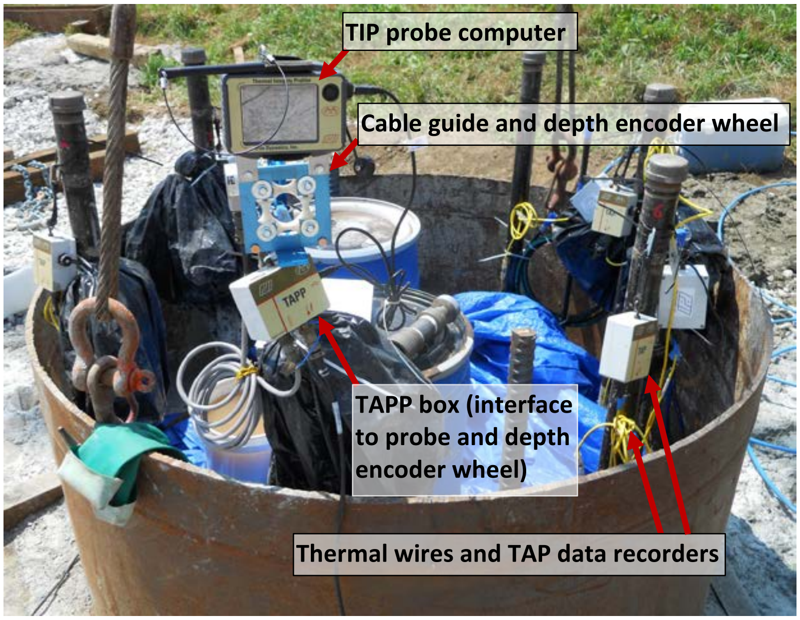

Figure 1: TIP testing and data collection on Test Shaft 4 using both probe and thermal wire methods (note 35-gallon drums for storing water from CSL tubes).

Figure 2: Close up of encapsulated temperature sensor and circuit board in PDI Thermal Wire® cable system.

Results

An example of TIP temperature profiles from Test Shaft 1 are shown in Figure 3. Also shown in the plots are radius profiles estimated from the temperatures, compared to the theoretical design radius and the radius calculated using concrete truck logs. The depth ranges of the defects and O-cell are shown in the figure as horizontal bands. For the specific types of prefabricated artificial defects used in this study, defects smaller than 4% of the shaft area did not always produce clear indications of anomalies in the test data, while larger defects were generally detectable by the nearby access locations (tube or wire). The theory was that since the prefabricated defects generate no heat, they would show up as a local reduction in the average shaft temperature, and thus a reduction in the equivalent shaft radius. Since the defects have lower stiffness than the shaft's concrete, they should also show up as reductions in velocity and energy in CSL tests, as long as they were located in a path between a pair of tubes. However, because of the size of the defects and the fact that they were generally tied to the rebar cage in the vicinity of two to three CSL access tubes, they were not always evident in plots of the average temperature (or radius) from all access locations at a given depth, but were generally more apparent as dips in the individual temperature profiles of the adjacent tubes or wires.

Additionally, data from the thermal wires revealed that the type of "cold" prefabricated defects used in this study were more clearly visible in TIP data on the heating side of the temperature curve than the cooling side. Once the defects were heated up, they were harder to detect by the probe tests, which were performed 20-24 hours after casting. Had the probe tests been performed after only 8 to 12 hours, it is likely that the defects would have been more strongly indicated as anomalies. Real defects may or may not behave similarly to the simulated ones used in this study, so use of TIP along with CSL in the same production shafts is recommended until a sufficient number of actual defects can be observed and compared to form a better judgment.

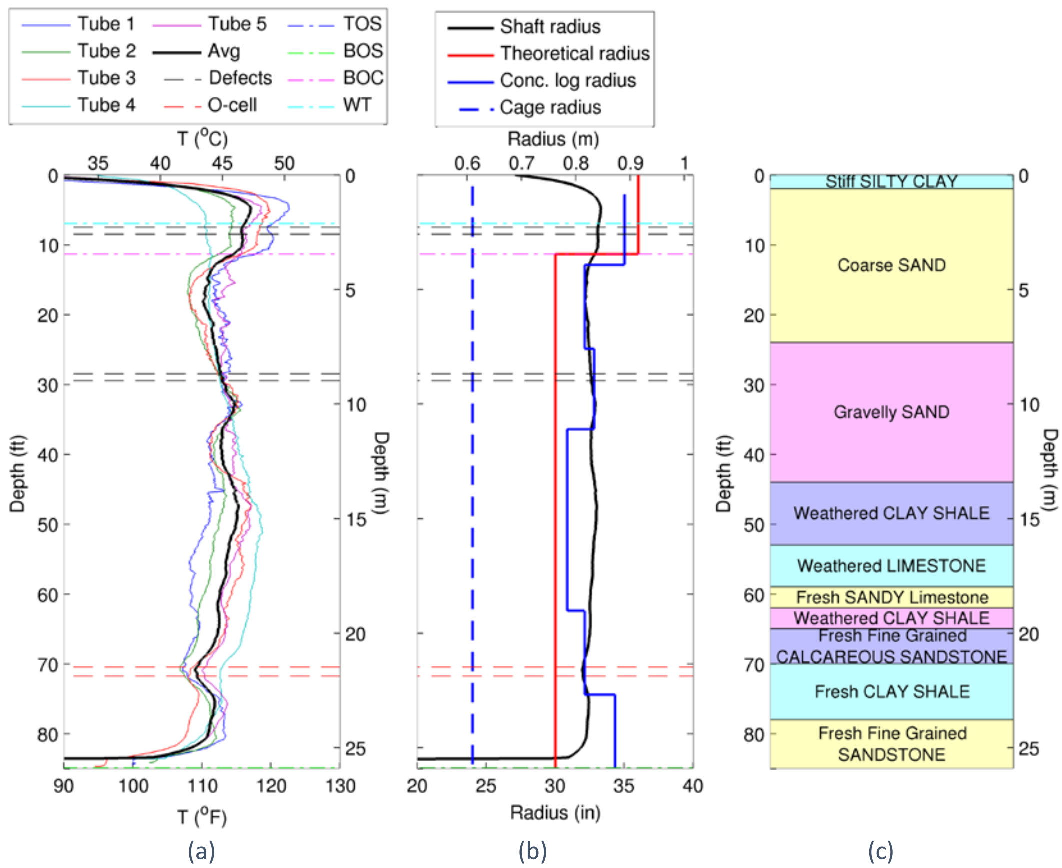

Figure 3 Thermal integrity profiling temperatures and soil profile for Shaft 1 (a) temperature; (b) apparent, theoretical, concrete log, and cage radii; (c) soil profile (from Ashlock and Fotouhi 2014)

Recommendations and Implementation

Potential benefits of using TIP for nondestructive quality assessment of drilled shafts include assessment of the entire shaft rather than the smaller volumes probed in CSL and GGL tests, and potential cost savings as a more economical alternative to CSL testing. The TIP method could also be used as a screening tool to identify which shafts should be further analyzed by CSL specialists. To help ensure that proper procedures are followed, the procedures and specifications in ASTM D7949-14 Standard Test Methods for Thermal Integrity Profiling of Concrete Deep Foundations should be followed. In addition to steel pipes, the ASTM standard allows plastic access ducts for the thermal probe method.

Based on the results of this study, the following are recommended regarding TIP tests and analysis:

1. As mentioned in ASTM D7949, if the same steel access tubes are to be used for TIP probe tests followed by CSL tests, then an appropriate means of minimizing temperature loss of the water while in the storage containers is recommended. Minimizing the water temperature difference between draining and refilling the tubes will help avoid any debonding of the CSL tubes upon refilling. In this study, water containers were covered by insulating blankets and tarps, and the water temperature was monitored with a thermometer. It has been reported that no adverse effects have been observed with water up to 30°F cooler than when it was removed. For the tests in this study, the water temperature difference was below 20°F.
2. When analyzing TIP data, do not focus only on the average temperature profile, but look for local dips in temperatures of the individual access locations. These will indicate the presence of anomalies that are only large enough to affect some of the nearby tubes or wires.

Advantages of using thermal sensor wires (ASTM D7949 Method B) over thermal probe (Method A):

1. **Continuous data:** The greatest advantage is that thermal wires provide continuous recording of data at all sensor locations, including both the pre-peak and post-peak portions of the temperature vs. time curve. This is valuable because according to this study, some of the manufactured defects produced a much greater temperature contrast with the surrounding concrete and during a portion of the heating rather than the cooling portion of the curve, and could be missed depending on the timing of the probe test. Additionally, the visibility of the defects of various sizes and types evolved over time. Defects were generally most noticeable at a certain point in time on the heating portion of the curve, before and after which they were smoothed out and might not be identified as an anomaly. In contrast, using the probe method provides snapshots of temperature profiles at only one point in time. When analyzing data from thermal wires, it is also recommended to observe animations of temperature profiles sampled at intervals of no more than 1 hour, rather than only selecting a few representative times to plot the profiles. In doing so, the thermal wires may help to catch some anomalies that may not be evident after the shaft heats up.
2. **Shorter preparation/testing time:** For the large shafts up to 6.5 ft in diameter and nearly 100 ft in length used in this study, the time required to measure the lengths, spacing, and stickup heights of all access tubes, dewater the tubes, wait for them to stabilize, perform probe tests with at least one repetition per tube as recommended by ASTM, and refill the

tubes can require up to 8 hours per shaft, even for an experienced pair of operators. In contrast, installation of the thermal wires during construction of the same shafts required only 1/2 day, plus 30 minutes to initialize and connect up to six data recorders. Probe testing time could be decreased significantly by using separate plastic or PVC access tubes that are not filled with water.

3. **Repeatability and lack of disturbance from testing procedure and weather:** Thermal sensor wires are cast into the concrete at the time of construction and simply measure temperature over time, with negligible disturbance of the concrete temperature by the sensors themselves. On the other hand, the thermal probe must be lowered into the access tubes slowly to minimize disturbance caused by the temperature of the probe itself, as well as the air it forces out of the tube. Additionally, windy conditions can cause even more rapid temperature loss inside the tubes near the surface. This can occasionally cause difficulty in meeting the ASTM recommended consistency of ±2°C between the initial and confirmation temperature profiles.

Advantages of using the thermal probe (Method A) over thermal sensor wires (Method B):

1. **Reusability without recurring costs:** The primary advantage of the thermal probe is that it is reusable and has no recurring costs other than repairs, whereas thermal wires are sacrificial and must be purchased for each new shaft tested. Thermal wires also require a one-time purchase of a dataloggers for each wire. Similar to requirements for CSL tubes, ASTM specifies one wire per foot of shaft diameter, therefore purchasing six dataloggers will be sufficient for testing shafts up to 6 ft in diameter. Purchasing six dataloggers will have a similar cost to purchasing a probe system. However, if TIP tests are eventually specified as an alternative rather than a complement to CSL tests, the present cost of thermal sensor wire (approximately $1 per foot) is comparable to that of typical 2-in. Schedule 40 pipe, and would therefore be offset by eliminating the pipe.
2. **Shorter unavailability during testing:** The dataloggers for thermal wires will generally be attached to a shaft for a few days, during which time they will be unavailable for use on other shafts. In contrast, the thermal probe is only unavailable for ½ to one day while it is being used to test a shaft, and can potentially be used to test one to two large shafts per day.

3. **Adjustable vertical resolution:** Another advantage of the probe is that that the vertical distance between the probe's sample points can be adjusted in the software of the TIP data recorder. If the operator notices an anomaly during testing, they could decrease the spacing between sample points and perform another test to gain better vertical resolution of the temperature profile. In contrast, the thermal sensors are at fixed intervals (typically 1 ft) that cannot be changed once they are cast into the concrete.

For implementation of TIP testing, it is recommended that the DOT specify TIP tests together with CSL tests on the same production shafts, until a sufficient number of defects are proven to be found by both techniques. As the DOT gains more experience and familiarity in interpreting results of TIP tests, they may consider TIP as a possible alternative to CSL testing, or as a screening tool to identify which shafts should be further analyzed by CSL specialists.

References

Ashlock, JC and MK Fotouhi, "Thermal Integrity Profiling and Crosshole Sonic Logging of Drilled Shaft with Artificial Defects", GeoCongres 2014, Geo-Characterization and Modeling for Sustainability, Atlanta, GA, Feb. 23-26, 2014, 1795-1805.

ASTM International. ASTM D7949-14 Standard Test Methods for Thermal Integrity Profiling of Concrete Deep Foundations. West Conshohocken, PA; ASTM International, 2014. doi: https://doi.org/10.1520/D7949-14