DRILLED SHAFT ACCEPTANCE CRITERIA BASED UPON THERMAL INTEGRITY PROFILING

George Piscsalko, Pile Dynamics, Inc., Solon, Ohio, USA, 216-831-6131, gpiscsalko@pile.com
Garland Likins, Pile Dynamics, Inc., Solon, Ohio, USA, 216-831-6131, glikins@pile.com
Gray Mullins, University of South Florida, Tampa, Ohio, USA, gmullins@foundation.cc

ABSTRACT

Quality control of drilled shafts is greatly dependent upon the practices of the site personnel. For drilled shafts cast under slurry, inspection of the hole prior to concreting is very difficult or impossible. There are numerous non-destructive test (NDT) methods currently available to assess the integrity of drilled shafts. This paper will discuss the theory and use of an emerging NDT technology known as Thermal Integrity Profiling (TIP). The Thermal Integrity Profiling method measures the elevated concrete temperatures that occur during the hydration process. These temperature measurements are made along the length of the pile and can determine the integrity over 100% of the pile cross section, both inside and outside the reinforcing cage. With the known shaft volume information, TIP can evaluate the effective shaft radius at each measurement location. With the increased use of TIP on highway projects, there is a need to have standard criteria for shaft acceptance. Shaft acceptance criteria can be based upon thermal measurements and subsequent analysis of the data to determine the average shaft radius, local concrete cover, and cage alignment. With this additional information obtained via the thermal testing method, acceptance methods based upon concrete cover can be developed. In this paper the Thermal Integrity Profiling method will be described, results from a case history will be discussed, and an acceptance criteria based upon concrete cover will be proposed.

INTRODUCTION

Drilled shafts are an attractive foundation element in many applications due to their large axial and lateral capacities. When drilled shafts are cast in a dry hole, it is possible to inspect the hole prior to casting, allowing for very basic level of quality control, although the shape of the completed element is still unknown without some form of post construction testing. When drilled shafts are installed where soil conditions are unstable, the shafts will often be cast under slurry to support the surrounding soils during the construction process. When casting a drilled shaft under slurry, it is very difficult to impossible to accurately and efficiently inspect the hole prior to casting concrete and it is equally difficult or impossible to inspect the shaft during the casting process.

There are several non-destructive testing methods available for testing the integrity of completed elements. Each of these methods has advantages and limitations with TIP being the only method able to test the entire element. Some test methods can test the integrity within a small proximity of an access tube while other methods will test the shaft core but cannot test the areas outside the reinforcing cage (concrete cover). The

TIP method involves measuring the temperature generated during the hydration process of the concrete both inside the cage as well as outside the cage.

This Thermal Integrity Profiling (TIP) method has the ability to evaluate the entire cross-section of the element under test, along the entire shaft length, allowing for verification of concrete quality or concrete cover while also evaluating the core of the shaft. Pile length to diameter ratios which can restrict some other integrity testing methods (such as low strain integrity testing) are not a restriction to the TIP method. Additionally, the TIP method is not limited by large non-uniform cross section changes that can occur by design or unintentionally during the construction process. As the TIP method determines the effective shaft radius and overall shape, designers now can better assess the usability of shafts where defects have been detected within the shafts. The inherent limitations with TIP testing are the time sensitive nature of the test, as the data must be collected during the hydration process as well as the need to cast sacrificial wires or access tubes into the shaft. This paper will discuss the TIP testing method in detail along with recommendations for acceptance criteria based upon reduction of both radius and concrete cover. An example will be included showing the TIP method in practice.

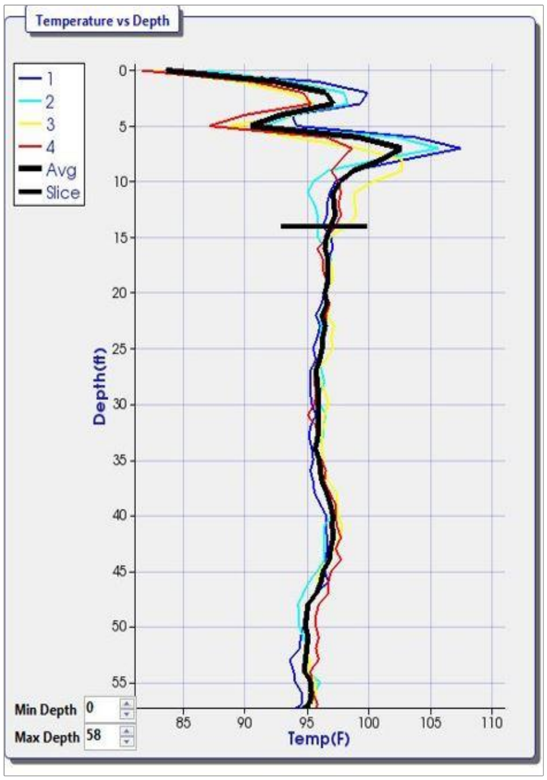
THERMAL INTEGRITY PROFILE BACKGROUND

The Thermal Integrity Profiling (TIP) method determines the integrity of a shaft both inside and outside the reinforcing cage by measuring the temperature of the hydrating concrete along the entire length of the shaft. The temperature measurements are made by either passing a thermal probe through a de-watered access tube (Mullins, 2004) or from embedding thermal cables (Piscsalko, 2011) within the shaft. At each depth all temperature readings are averaged together and, along with the total volume data, used to determine the overall shape of the shaft as a function of depth (Sellountou, 2013). The accuracy of the effective radius calculation is dependent upon the accuracy of the volume data.

Curing concrete exhibits a normal heat signature with shaft temperatures dependent upon the shaft diameter, concrete mix design, concrete quality, and (to a lesser extent) soil conditions. Insufficient cement content (defect) will cause a local reduction in temperature near the defect. For smaller diameter shafts, a defect may be detected on the opposite side of the shaft. Any temperature measurements which are cooler than the overall average are areas of reduced concrete volume (defect) or poor concrete quality and any area with a higher temperature than the average are areas of increased concrete volume (typically a bulge). The example shown in Figure 1 has temperature measurements for a small diameter shaft which would indicate a defect located closer to wires 3 and 4 at a depth of 5 feet below top of shaft (the normal temperature signature is reduced more at wire locations 3 and 4 as compared with wire locations 1 and 2).

In addition to determining concrete integrity, the TIP test will also reveal any potential issues with reinforcing cage alignment by comparing TIP measurements from radially opposite locations versus the average value. If a single measurement location is cooler or warmer than the average and the radially opposite location behaves in an opposite manner then the cage is not concentric within the shaft. For example, if a first measurement location is warmer than the average this indicates that this location is closer to the shaft center, and if a second diagonally opposite measurement location is cooler than the average this indicates that this location is closer to the surrounding soil, so thus the cage is not concentric with the hole.

In short, the average temperature profile (from all wires or tubes) defines the shape of the shaft and local variations from the average indicate cage offsets from center.



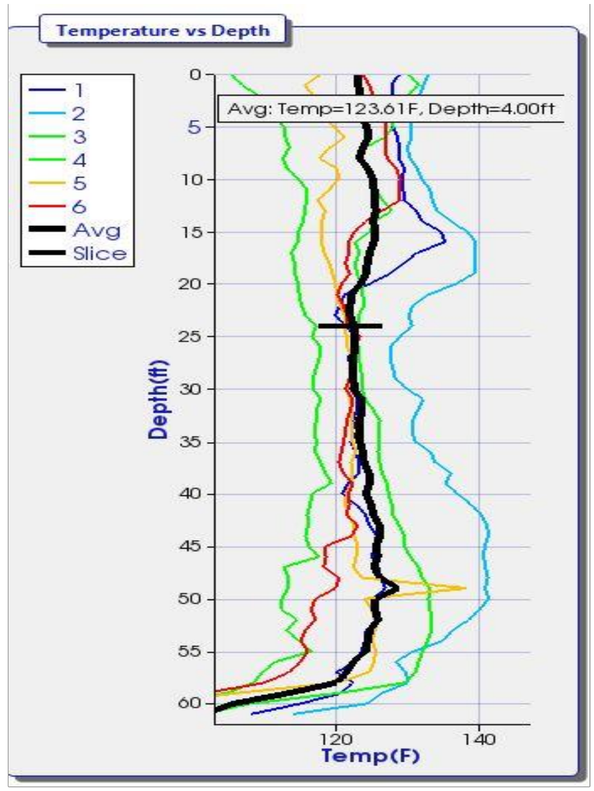


Figure 1

Figure 2

When considering both these measurements together, it can be determined that the cage has shifted such that location one is closer to the shaft center and location two is closer to the surrounding soil. Figure 2 shows wire 2 being consistently warmer than the average (wire 2 is closer to the warmer center of the shaft) while wire 4 is consistently cooler than average (wire 4 is closer to the cooler surrounding soils). This gives additional information on concrete cover. There is reduced concrete cover at wire location 4.

The recommended number of measuring locations (e.g. access tubes or thermal wires) per ASTM D7949 is one per foot of shaft diameter (e.g. 10 thermal cables installed for a 10 foot diameter shaft) and spaced approximately equally around the reinforcing cage perimeter. It is recommended that an even number of tubes or wires be installed, with pairs being placed diametrically opposite one another to enable lateral movement, if any, of the reinforcing cage to be easily determined. The TIP method will then easily determine the complete shaft cross-section and along with the volume data, can generate a three dimensional image of the shaft.

Generally heat transfer away from the shaft is only radial along the length of the shaft. However at the top and bottom of the shaft the heat transfer is both radial and longitudinal and thus the temperatures are typically reduced at the top and bottom ends of the shaft. This top and bottom of shaft temperature reduction (roll-off), typically seen in a thermal integrity profile, has a hyperbolic tangent shape. Knowing this characteristic roll-off shape allows for an adjustment to be applied to the thermal measurements at the top and bottom of the shaft (Johnson, 2015). When the adjustment is applied to the shaft top and bottom, the roll off portions of the adjusted curve then match the theoretical interior measurements (curves generally flatten out). When end bearing is to be included in the shaft design, the values used for the roll-off correction at the shaft bottom should be carefully chosen such that the true shape of the shaft bottom and any anomalies are properly depicted. Once the top and bottom of the curves have been adjusted, the analysis in these areas is similar to the remainder of the measurements made along the length of the shaft.

The TIP measurements are obtained using Thermal Wire cables which are attached to the reinforcing cage prior to cage insertion into the shaft. The TIP wires are embedded directly into the concrete, placing one wire for each one foot of shaft diameter (6 foot diameter shaft will have 6 wires), equally spacing the wires around the shaft. These cables have temperature sensors placed every foot vertically along the length of the cable. Once the concrete has been placed in the shaft, the cables are connected to special purpose data loggers. The thermal measurements are taken automatically at regular time intervals (usually approximately every 15 minutes) at least until the shaft has reached its peak temperature.

Alternately, TIP measurements can be obtained using a thermal probe passed through de-watered access tubes installed in the shaft. These tubes can be steel or plastic. The test will be performed typically 12 to 48 hours after completion of the shaft. The optimum time is dependent upon the shaft diameter and mix design. Optimum results are obtained between a time when concrete temperature is one half peak temperature to a time shortly after peak temperature. The test is performed by lowering the probe into the access tube at a rate of no more than 0.3 ft/sec, recording and averaging all temperatures from four infra-red temperature sensors located at every 90^0 radially around the probe

Using the concrete volume installation records and the total measured concrete volume, the overall average temperature is correlated to the average radius. Once this average temperature to average radius correlation has been established, the effective radius at any point along the shaft can be directly calculated. The effective radius is considered to be the radius of intact good quality concrete that would have exhibited the measured temperature. This effective radius is computed directly from the relationship of shaft volume placed, shaft length, and the average overall shaft temperature measured from all locations and depths. The effective radius is best evaluated at approximately the time of peak temperature. The time of peak temperature is not known a priori, but may be estimated from the mix design. A search for local defects is best made at the time after casting is complete that is only halfway to the peak temperature; the temperature versus time history for the TIP wires can be searched.

EVALUATION OF THERMAL INTEGRITY PROFILING TEST RESULTS

Shaft acceptance criteria based on thermal integrity profiling extends current practices by now knowing the average shaft radius, local shaft cover, and cage alignment (eccentricity). Therefore acceptance can consider all aspects of load carrying capacity as well as durability afforded by the concrete cover thickness. To this end, a broad specification may cover a majority of probable conditions but more refined considerations may be more appropriate for a given project and are available for evaluation by the design team.

The load carrying requirements of drilled shafts can be controlled by geotechnical side shear (most common) or structural bending and/or compression. These are directly related to the circumference surface area of the shaft, the moment of inertia, and the cross sectional area, respectively. Using a percent radius reduction approach means that each will be affected differently; circumference linearly related, moment of inertia effects based on reduction raised to the fourth power, and area effects related to the square of the reduction. Figure 3 shows these effects irrespective of shaft diameter but where the loss of section is assumed in the worst case position, outside the cage.

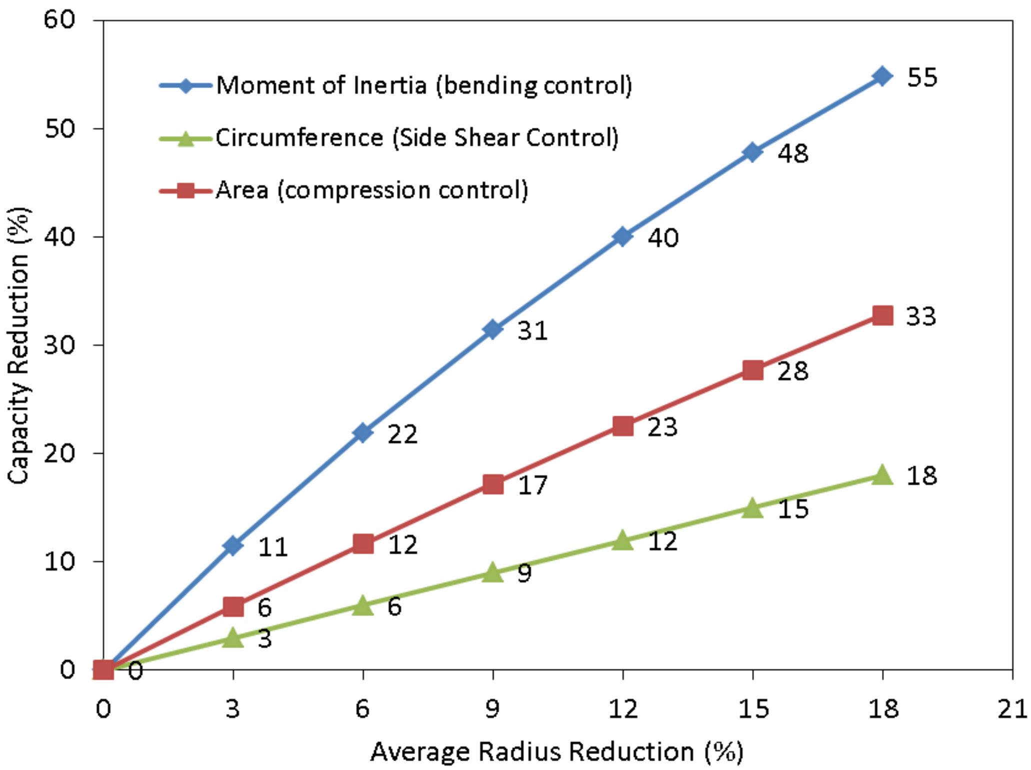


Figure 3

While the average radius is an indication of the cross sectional properties, the local radius is a better indication of the concrete cover and cage alignment/eccentricity. For highway bridges, the AASHTO recommended minimum cover of 4 inches is often used throughout the U.S.A., but individual states have adopted different acceptance criteria based on local needs or conditions.

However, private or commercial designers and some state agencies allow a design concrete cover of 3 inches, which is the ACI minimum cover for foundations cast-in-place. While this was intended for spread footings poured on-grade, many use this criterion for deep foundations as well. Figure 4 shows the effect of two cover loss considerations on the local radius reduction. If a 1.5 inch of remaining cover is acceptable, but with a design cover of 3, 4, or 6 inches, the permissible maximum local radius reduction is given. If 2 inches of remaining cover is the permissible criterion (ACI exterior concrete minimum for above ground applications), and an initial cover of 4 inches is assumed, then that effect is also shown.

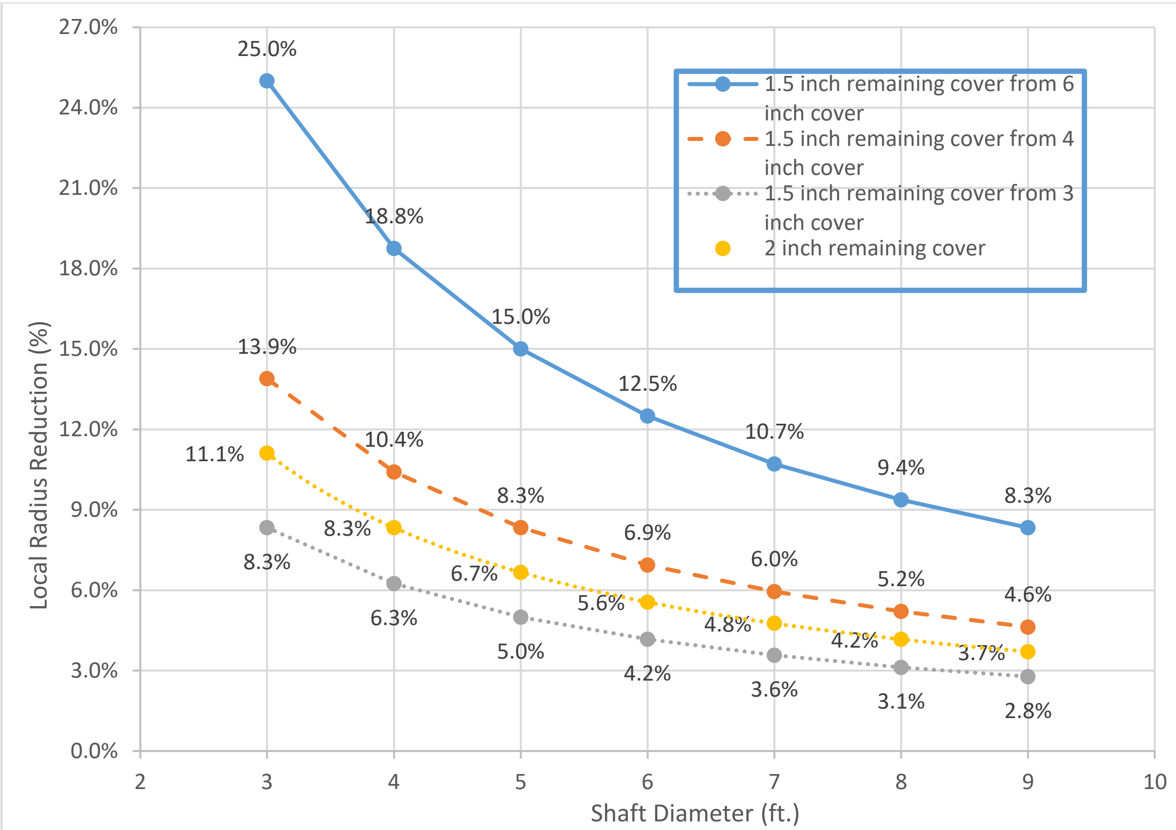


Figure 4

In reality, a 3 inch design cover provides no leeway for error as any cage movement in a perfectly-sized shaft impinges on the minimum cover for cast-in-place concrete and the 2 inch ACI minimum for above ground, exterior conditions is not applicable.

If a 0 to 6% and above 6% radius reduction criteria is applied to shafts as satisfactory and questionable respectively, the net effect on shaft properties can be summarized in Table 1.

Table 1. Effect of radius reduction on various shaft performance indicators.

Radius Reduction	Bending Capacity Loss	Compression Capacity Loss	Side Shear Reduction	Cover Loss (4 inch cover, 6ft dia. shaft)
3%	11%	6%	3%	1.08in
6%	22%	12%	6%	2.16in
>6%	>22%	>12%	>6%	>2.16in

Based on the above considerations acceptance criteria can be implemented as:

Satisfactory (S)

0 to 6% Radius Reduction and

Local Cover Criteria Met

Anomaly (A) Requiring further evaluation

Radius Reduction > 6% or

Local Cover Criteria Not Met

When a tested shaft is categorized as Anomaly (A), evaluation of a horizontal slice, estimated from the TIP measurements at the location in question should be required so that a structural evaluation of the shaft be performed prior to implementation of any corrective measurements. Once a shaft is categorized as having an anomaly, all other possible information on the shaft construction as well as soil boring logs should be fully vetted along with the TIP results to determine acceptance of the shaft.

TIP CASE HISTORY

TIP testing was performed on all production shafts for a project in Washington State. TIP was the only testing method used on this project. The 10 ft. diameter shaft was 125 ft. long. There were ten TIP wires installed in the shaft. The TIP testing began immediately upon completion of concreting the shaft and continued for 120 hours.

The TIP test results indicated a sharp temperature reduction (anomaly) approximately 90 feet below the pile top (Figure 5). Analysis was done approximately 40 hours after casting was completed. After inputting the volume data, the TIP temperature data was converted into effective radius (Figure 6).

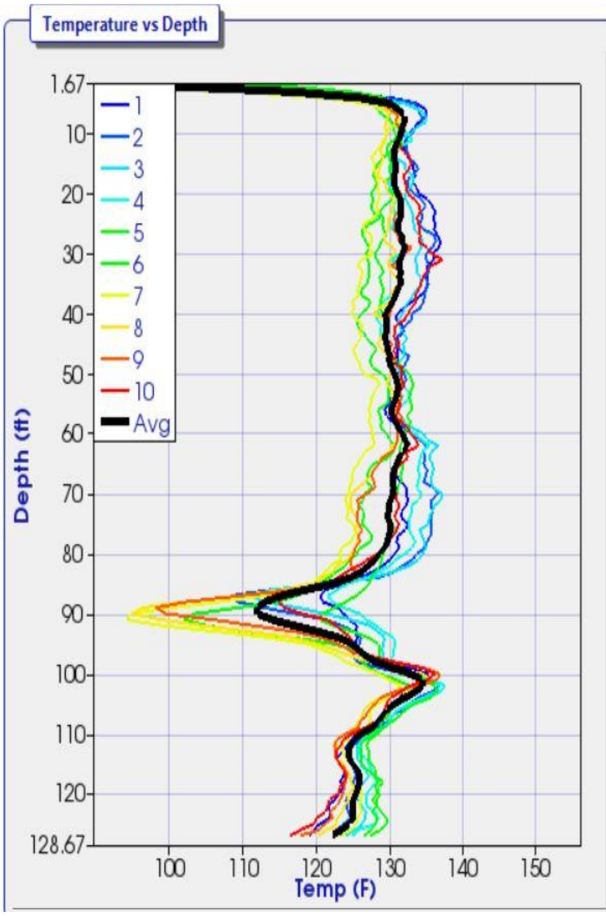


Figure 5

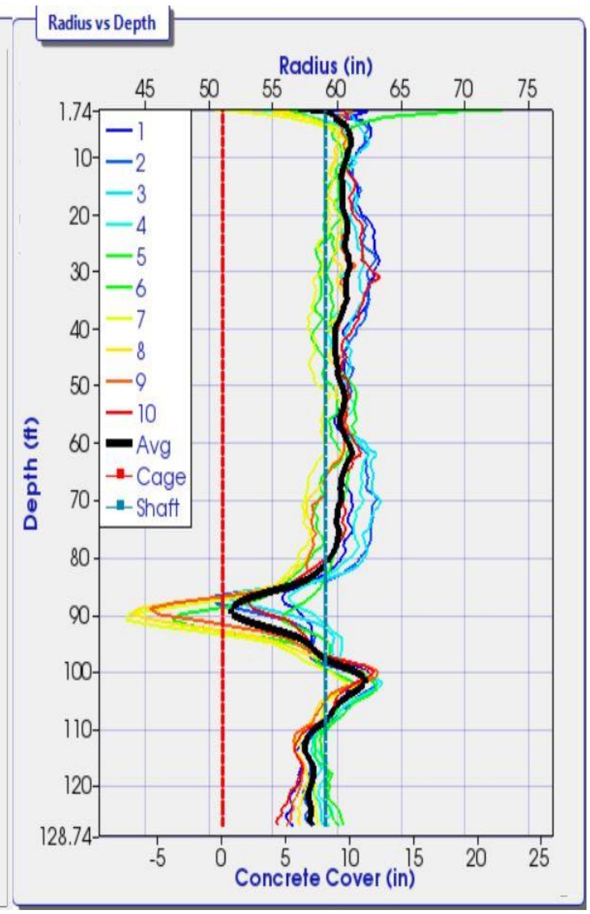


Figure 6

Figure 6 shows the effective radius and concrete cover as a function of depth. The concrete cover on one side of the shaft (wire locations 6 through 10) at a depth of 90 feet was less than the minimum allowable concrete cover (6in) and the total reduction in radius at this location is 14.2% and thus this shaft should be classified as Anomaly under either the radius reduction or minimum concrete cover criteria and warrants further evaluation in that zone. Some wire locations at that depth show the defect extended well inside the cage. The percent radius reduction in this region was 14.2%, resulting in a reduction of 26.3% in the cross-sectional area, which also triggered structural and geotechnical concerns along with the cover durability issue. Further evaluation included coring of the shaft which confirmed the defect present at this location identified by the TIP testing (Figure 7). The coring location was approximately 6 inches inside the reinforcing cage and located between TIP wires 7 and 8, which was the location the TIP testing revealed as having the greatest loss in effective radius. The defect was repaired using pressure grouting, saving the project from a potentially costly foundation failure.

Figure 7

CONCLUSIONS

The general trend in the deep foundation industry has been an increase in the use of drilled shafts. These shafts are often installed with little or no knowledge of the final shaft integrity, particularly when cast under a slurry, and to minimize concerns and reduce risk of failure, NDT methods are usually employed to investigate their structural integrity. Many common current NDT methods can each provide partial information as to shaft integrity, but each method also has limitations. The TIP method measures the shaft temperature during the hydration process to make an assessment of the shaft integrity. From these temperature measurements, the effective shaft radius can be estimated. The TIP method allows for assessment of 100% of the shaft cross-section, including concrete cover, which no other single current method can provide. Additionally, the cage alignment can be investigated and the concrete cover evaluated from the TIP data. Frequently the results of the TIP test are completed within 12 to 48 hours after the shaft has been cast, which is a major advantage over current methods as this can accelerate the construction process.

With the increased use of TIP on drilled shaft projects, there is a need to harmonize the acceptance criteria used. As shown from the included example, TIP can effectively locate defects within a shaft and can provide the designers with the radius reduction associated with these defects and allow for clear determination on when a shaft requires further analysis based on the acceptance criteria proposed in this paper.

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