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Evaluating the Accuracy and Use of Drilled Shaft Integrity Testing Methods in Illinois

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16. Abstract In this project, thermal integrity profile (TIP) and crosshole sonic logging (CSL) tests were performed on three test drilled shafts in three locations in Illinois to determine which technology is more effective at identifying installed defects in drilled shafts. TIP testing was found to be more effective than CSL in identifying installed defects outside the rebar cage. Conversely, CSL was found to be better than TIP at identifying installed defects at the bottom of the drilled shaft. A comprehensive cost analysis for TIP and CSL testing was performed using data from historical Illinois projects. The cost analysis showed that the costs of TIP and CSL testing were comparable. The findings of this research resulted in the creation of a decision flowchart that can be used to assist in the selection of nondestructive testing technology for drilled shafts in Illinois. Based on the project results, Illinois Department of Transportation's TIP and CSL specifications and construction inspector's checklist were modified to improve use of these tests.					
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EXECUTIVE SUMMARY

This report presents results for the research project titled “Evaluating the Accuracy and Use of Drilled Shaft Integrity Testing Methods in Illinois.” In this project, the research team focused on evaluating the effectiveness of drilled shaft integrity testing, including thermal integrity profile (TIP) and crosshole sonic logging (CSL) testing, to determine which technology is more effective at identifying installed defects in three test drilled shafts in Illinois. Three test drilled shafts with pre-planned defects were constructed, and two nondestructive test methods—TIP and CSL testing—were performed on the drilled shafts by consultants that had no knowledge of the installed defects to evaluate their effectiveness. The first test drilled shaft had additional Shaft Quantitative Inspection Device (SQUID) and Shaft Area Profile Evaluator (SHAPE) testing performed during its construction. A comprehensive cost analysis for TIP and CSL testing performed using data from historical Illinois projects showed the costs of TIP and CSL testing were comparable. The results of this projects led to the creation of a simple decision flowchart that can be used by the Illinois Department of Transportation (IDOT) in selecting the appropriate testing for drilled shafts in Illinois. Based on the project’s results, the IDOT TIP and CSL specifications and the Construction Inspector’s Checklist were modified to improve use of these tests.

The main objectives of this study were to evaluate CSL and TIP testing to determine which technology is more effective in identifying typical defects in drilled shafts, quantify historical Illinois costs related to integrity testing and remedial actions on Illinois drilled shaft projects, and use this data to provide guidelines on the appropriate use of integrity testing considering project size, construction method, drilled shaft size, and design redundancy.

Summary of Field Testing

Three test drilled shafts were constructed in Illinois at three separate locations, and integrity testing was conducted on these drilled shafts. The following is a summary of the dimensions, defects, and testing for each test drilled shaft:

- Drilled shaft #1 was constructed along I-72 in Macon County, Illinois, with a 4 ft diameter drilled shaft in soil, 3.5 ft diameter steel reinforcing (rebar) cage, a total length of 50 ft with no rock socket, and wet method concrete pouring. TIP, CSL, SQUID, and SHAPE tests were performed on drilled shaft #1 with four TIP wires and four CSL access tubes installed (one per foot of drilled shaft diameter). Drilled shaft #1 had the following pre-planned defects: soft toe, two tremie pipe raises, and a shifted rebar cage.
- Drilled shaft #2 was constructed along IL-47 in Kendall County, Illinois, with a 6 ft diameter in overburden soil, 5.5 ft diameter in underlying rock, 5 ft diameter rebar cage, a total length of 25 ft with a 15 ft long rock socket, and dry method concrete pouring. TIP and CSL tests were performed on drilled shaft #2 with 12 TIP wires (two per foot of drilled shaft diameter) and 6 CSL access tubes (one per foot of drilled shaft diameter). Drilled shaft #2 had the following pre-planned defects: two soil inclusions in rock socket and soil added to drilled shaft annulus between the rebar cage and temporary casing at the top of the shaft.

- Test drilled shaft #3 was constructed along IL-47 in Grundy County, Illinois, with a 4 ft diameter in overburden soil, 3.5 ft diameter in rock, 3 ft diameter rebar cage, a total length of 42.5 ft with a 5 ft long rock socket, and wet method concrete pouring. TIP and CSL tests were performed on test drilled shaft #3 with eight TIP wires (two per foot of drilled shaft diameter) and four CSL access tubes (one per foot of drilled shaft diameter). Test drilled shaft #3 had the following pre-planned defects: soft toe and two tremie pipe raises above the top surface of the concrete during concrete placement resulting in discharging fresh concrete through water or slurry.

Note: In this report, unless stated otherwise, the term “tremie pipe raise” indicates that the concrete pipe was raised above the top surface of the concrete during concrete placement resulting in discharging fresh concrete through water or slurry.

Summary of TIP and CSL Strengths and Weaknesses

A summary of the strengths and weaknesses of TIP and CSL testing is presented below.

TIP Strengths

- TIP testing is effective at identifying defects resulting from large tremie pipe raises in wet drilled shaft construction.
- TIP testing is somewhat effective at assessing rebar cage concrete cover for side resistance evaluation.
- TIP testing is effective at identifying soil inclusions that encroach inside rebar cage.
- TIP results can be available within two days of concrete pouring.

TIP Weaknesses

- Due to temperature decrease or roll-off at the top and bottom of the drilled shaft, TIP is not as effective at identifying anomalies near the top and bottom of shafts.
- TIP testing provides limited information at the center of large diameter drilled shafts.
- A shaft extending into a river with flowing water around the casing may influence temperature results and make it hard to identify defects, and therefore, a numerical analysis might be needed for this or other special cases.

CSL Strengths

- CSL testing is effective at assessing the condition at the drilled shaft bottom; for example, it can identify an uncleaned rock socket.

- CSL testing is effective at assessing the concrete at the center of the drilled shaft inside the surrounding rebar cage.
- CSL testing is effective at identifying soil inclusions and voids in the drilled shaft center.
- CSL testing is effective at identifying defects resulting from large tremie pipe raises in wet drilled shaft construction.
- CSL tests can be repeated on the same shaft if necessary to verify results, investigate anomalies further using offset tomography, or to verify post-remediation improvements.

CSL Weaknesses

- CSL tubes might be damaged due to bending during lifting of long rebar cages and insertion into the drilled shaft, which could allow concrete inside the CSL tubes, preventing the CSL equipment from accessing the full length of the drilled shaft. Therefore, personnel must ensure access tube joints are securely sealed during cage insertion, and access tube joints may need to be replaced if they are damaged.
- CSL testing does not provide information about concrete cover outside the rebar cage or rebar cage misalignment.
- CSL testing is typically performed three to seven days after concrete pouring and is typically done no later than 21 days. The longer the time, the more chance of tube debonding in the upper tube areas due to bumping of the tubes or large temperature swings. Therefore, the reviewer should consider this if anomalies show up near the top of the shaft. Nevertheless, CSL can be done even after 21 days, if needed, as long as tube debonding is considered during analysis of the data.

Decision Flowchart

The drilled shaft testing decision flowchart, shown in Figure 39, was developed by the research team as a guide for selecting nondestructive integrity testing for their project. The test method selection is based on drilled shaft diameter and drilled shaft design, i.e., whether the drilled shaft is designed as end bearing, a combination of end bearing and side resistance, or only side resistance. Please note that this flowchart is a guide, and users should use engineering judgement to make a final decision on CSL and TIP testing.

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CHAPTER 1: INTRODUCTION

PROBLEM STATEMENT

The use of drilled shafts as foundation units for Illinois bridge structures is increasing. Over a five-year period (i.e., 2007–2012), IDOT’s annual expenses for driven pile foundation systems was approximately constant at about \$12 million per year. However, over the same period, the use of drilled shafts increased from less than \$0.5 million per year to almost \$6.5 million per year because of lower unit cost, flexibility during construction, widely available material and equipment to construct, many qualified contractors, increased steel piling costs, and increased lateral load capacity and scour resistance of drilled shafts.

A drilled shaft involves drilling a cylindrical hole (typically down to a stiff soil layer or bedrock), placing a reinforcing steel (rebar) cage into the completed hole, and filling the hole with concrete to complete the drilled shaft. When water is not present in the drilled hole, i.e., the dry method, the quality of the drilling and concrete in the drilled shaft is usually less of a concern but significant cuttings can be left in the bottom of the drilled shaft, which results in a soft bottom condition and leads to reduced end bearing resistance and excessive settlement of the drilled shaft. However, with water or drilling slurry present in the hole, i.e., the wet method, or when a temporary casing is used to support the shaft excavation with the dry method, it is difficult to ensure final shaft quality because visual inspection is limited or even impossible. As a result, some states are using various methods of integrity testing for acceptance of drilled shaft construction.

Drilled shafts are traditionally designed using empirical predictive methods that were developed based on axial load tests in similar soils or rocks. These methods often have a certain degree of uncertainty due to their empirical nature and different subsurface conditions. Resistance factors, which are developed for a given target reliability, are used to compensate for these uncertainties. However, all these methods assume the drilled shaft is well constructed, the bottom of the drilled shaft is free of debris before concrete pouring, and sufficient concrete encapsulates the rebar cage in the drilled shaft. As a result, it is important to properly construct, closely inspect, and if necessary, nondestructively test the drilled shaft to ensure the drilled shaft is intact and the empirical design methods are applicable before allowing the bridge construction to progress.

Prior to development of nondestructive test methods, performing axial load tests on drilled shafts was the primary means to assess the accuracy of the empirical design methods for side and tip or end resistance as well as construction of the drilled shaft. However, only major projects can afford the cost of conducting axial load tests on drilled shafts for assessing the axial capacity and settlement design requirements. Drilled shaft load tests may not be justified for smaller projects, including bridge pier construction or replacement, where the cost of load tests would be a significant percentage of the total cost of the project. As a result, nondestructive tests are being developed to assess the integrity and construction of drilled shafts without load testing prior to contract acceptance of the drilled shaft by the engineer.

A common method used for drilled shaft integrity testing is crosshole sonic logging (CSL). CSL is probably the most well-established drilled shaft integrity testing method (ADOT, 2007; Mullins and Kranc, 2007). CSL testing involves the measurement of the compression wave velocity ($V_{p\text{-wave}}$) on horizontal planes at regular depths along the drilled shaft. The CSL access ducts, i.e., open steel or plastic access ducts (tubes) or pipes, are installed inside the reinforcing cage and the testing is used to assess concrete quality between the access ducts, i.e., inside the reinforcing cage, based on the measured compression wave velocity, first arrival time, and relative energy or signal intensity.

A Federal Highway Administration (FHWA) and WisDOT joint report (Broeckmann & Loehr, 2015) identified several emerging technologies, such as thermal integrity profile (TIP) testing, as viable nondestructive tests for evaluating and improving drilled shaft construction. In particular, TIP testing can nondestructively assess drilled shaft integrity before contract acceptance by measuring the heat of concrete hydration temperatures at different times with respect to depth within the drilled shaft, as described below. TIP testing was introduced several years ago by Gray Mullins of the University of South Florida (Mullins & Kranc, 2007; Mullins, 2010; Mullins & Winters, 2011).

Drilled shafts are frequently constructed under conditions such that visual inspection of the drilled shaft sidewalls, bottom, reinforcement location, and concrete placement cannot be performed. This can be due to the drilled shaft being constructed underwater or the safety concerns of lowering a person into the drilled shaft to inspect the sides and bottom. Integrity testing allows for assessment of the completed drilled shaft to ensure that no detrimental flaws were created during construction of the drilled shaft. Evaluating the different integrity tests for drilled shafts will allow IDOT to use the most effective method and have confidence that the chosen method accurately determines the integrity of the drilled shaft before continuing with construction of the remaining portions of the structure. More importantly, integrity testing allows the owner to determine if the completed drilled shaft will safely support the applied loads. Embracing this type of testing would allow IDOT to make real-time decisions about accepting a drilled shaft.

In particular, CSL and TIP testing are evaluated directly in three field test drilled shafts to determine which technology is more effective in identifying typical defects in constructed drilled shafts. This research also quantified historical Illinois costs related to drilled shaft integrity testing and remedial actions on Illinois drilled shaft projects and evaluated the cost effectiveness of requiring CSL and TIP testing for future IDOT drilled shaft construction. A recent FHWA report (Boeckmann & Loehr, 2015) summarizes integrity testing of 13 transportation agencies surveyed and shows that 6 of the 13 agencies have used TIP testing. Brent (2012) has shown that 32 state DOTs use CSL testing.

Scope of This Research

The scope of this research is as follows. First, evaluate CSL and TIP testing to determine which technology is more effective at identifying typical defects in Illinois drilled shafts. Second, quantify historical Illinois cost data related to integrity testing and remedial actions on Illinois drilled shaft projects. Third, use this data to develop guidelines on the most appropriate use of integrity testing considering project size, construction method, drilled shaft size, and design redundancy. To implement the results of this research, a simple flowchart was developed to determine when and what to specify for integrity testing of drilled shafts. The following presents a description of the six

main tasks that were performed to achieve the overall project objective of evaluating the effectiveness of drilled shaft integrity testing for IDOT projects:

1. **Literature Review:** Conduct a literature review covering CSL, TIP, and other integrity test methods.
2. **Data Collection:** Collect statewide project-specific cost data on historical integrity testing and summarize the results in Chapter 3.
3. **Test Program Development:** Develop an experimental program designed to compare the accuracy of CSL and TIP testing at identifying typical defects encountered in Illinois drilled shafts. This test program involved construction of three test drilled shaft foundations with intentional “pre-planned” defects in Illinois.
4. **Implementation of Experimental Program:** Construct the three test drilled shafts with the pre-planned defects, conduct TIP and CSL testing, analyze the test results, and make recommendations on the use of integrity testing for future IDOT projects. (Two consultants performed the CSL and TIP testing and are referred to as “Consultant A” and “Consultant B” in this report).
5. **Development of a Flowchart for Selecting Drilled Shaft Integrity Testing:** Develop a decision flowchart to help designers select appropriate integrity testing for drilled shafts. The decision flowchart is to be incorporated into IDOT’s *Bridge Manual*.
6. **Final Report:** Prepare a final report that summarizes the outcome of this research, including recommendations for policy and specifications improvements.

CHAPTER 2: SUMMARY OF THE LITERATURE REVIEW AND METHODOLOGY

Nondestructive integrity tests were originally developed as a quality assurance tool for precast driven piles and foundations constructed using techniques where portions of the construction could not be visually inspected, which is commonly referred to as “blind” construction. This testing is used because driving concrete piles can result in damage to the pile even though the pile was factory fabricated and inspected before shipment to the project and driving. Conversely, drilled shafts are constructed on-site, so all inspection and testing must be conducted during field construction.

In drilled shaft construction, the presence of drilling slurry or water prevents visual inspection of the drilled shaft bottom, sidewalls, reinforcing bars, and concrete placement. Even without drilling slurry or water, visual inspection of the drilled shaft bottom, sidewalls, and concrete placement is difficult. The blind nature of drilled shaft construction, especially under slurry or water, leads to uncertainties related to whether the constructed foundation element will perform as the designer intended. No single integrity test method, destructive or nondestructive, can provide complete information on the integrity of a drilled shaft foundation. As a result, drilled shaft foundation projects commonly require careful construction, close inspection, and may also include the use of one or more types of integrity testing methods. For example, it is common in California to perform both Gamma-Gamma logging and crosshole sonic logging to evaluate the integrity of the concrete cover over the reinforcing steel cage and the concrete inside of the reinforcing steel cage, respectively, for drilled shaft construction (Liebich, 2004).

This chapter presents a summary of the literature review that is presented in Appendix A. The literature review in Appendix A addresses the means, methods, equipment, basic analyses, and key advantages and disadvantages of the commonly used integrity testing methods for drilled shaft construction. This literature review provides background information for this research project. The literature review focuses on commonly used nondestructive test methods, equipment, materials required for testing, and key advantages and disadvantages of each of these integrity test methods. Listed in order of appearance in Appendix A are the following drilled shaft integrity tests: crosshole sonic logging (CSL), sonic echo testing (SET), impulse response testing (IRT), Gamma-Gamma logging (GGL), concreteoscopy (CT), parallel seismic integrity testing (PSIT), and thermal integrity profiling (TIP). Additional information on drilled shaft integrity testing is available in Brown et al. (2010).

Table 1 provides a brief comparison of TIP, CSL, sonic echo, impulse response, and Gamma-Gamma test methods. There are also limitations to the analysis of TIP testing, such as the occurrence of decreasing temperature or roll-off at the top and bottom of the drilled shaft and limited ability to detect defects in the center of the drilled shaft, which can be detected by CSL. However, CSL cannot detect defects outside of the reinforcing cage because the access tubes are installed inside the reinforcing steel cage. When interpreting the test data, detrimental defects need to be distinguished from nuisance effects, such as small increases in diameter. The test window closes within days of concrete placement for TIP testing, so the optimal test time varies with drilled shaft diameter and boundary conditions like the concrete batch ingredients, depth to water table, and type of soil.

Table 1. Summary of Ability to Detect Small- to Modest-Sized Defects Using Nondestructive Test Methods (Mullins & Winters, 2011)

Type of Drilled Shaft Defect	Ability to Detect Relatively Small to Modest Defects ^[*]			
	Thermal Integrity Profiling	Crosshole Sonic Logging	Sonic Echo/Impulse Response ^[**]	Gamma-Gamma
Inclusions in cage interior	Difficult to detect	Readily detectible	Marginally detectible	Detectible
Defects outside reinforcing cage	Readily detectible	Not detectible	Not detectible	Detectible
Soft bottom	Possibly detectible if accurate measurement between bottom of drilled shaft and bottom thermal sensor	Detectible	Not detectible	Detectible
Weak concrete	Detectible	Difficult to detect	Marginally detectible	Detectible
Breach of tremie pipe	Potentially detectible	Detectible	Marginally detectible	Detectible if near sensor and access tube

* Detection ability assessments are generally based on small to modest defects in the drilled shaft. Detection ability is likely better for larger drilled shaft defects.

** For sonic echo/impulse response potentially all of these types are not detectible for small to modest defects but are detectible if the defects are large (>15% of drilled shaft area).

METHODOLOGY

TIP Testing

One consultant performed TIP testing for all three test drilled shafts and will be referred to in this report as “Consultant A.” The TIP test results can be used to evaluate drilled shaft shape and integrity, concrete quality, and location of the rebar cage. TIP testing was performed by means of thermal wire cables and thermal acquisition ports (TAPs) in accordance with ASTM D7949. The TIP system, manufactured by Pile Dynamics in association with Consultant A, records concrete temperatures during curing using cables embedded in the concrete. The objective of TIP testing is to evaluate the concrete and drilled shaft construction after installation. The TIP data summarized in this chapter was recorded by Consultant A from September 23 through 27, 2019.

The thermal wire cables consist of temperature sensors spaced every one foot along the delivered length of a wire. For test drilled shaft #1, four thermal wires were attached approximately symmetrical around the rebar cage. The thermal wires extend the full length of the drilled shaft rebar cage. Once the rebar cage was set in the drilled shaft and concrete was placed, a TAP box was attached to each wire to record the temperature of concrete during the curing process. During concrete curing, the hydrating cement generates heat, which increases the temperature in the drilled shaft. Every 15 minutes, the TAP units automatically record the measured temperature at each sensor location along the length of the wire, which is used to generate a profile of temperature

versus depth at each increment of time. The temperature data is remotely transmitted to a server for review and retrieval. After the peak concrete temperature has been achieved, the data is downloaded for further interpretation.

Consultant A assessed drilled shaft integrity using the TIP data by relating the overall average temperature for all thermal wires over the embedded depths to the overall volume of concrete installed. Consultant A's drilled shaft integrity assessment is based on the average temperature measurements from each thermal wire at each depth increment. If the measured average temperature versus depth is consistent, then the drilled shaft is considered of uniform shape and quality. Bulges can be identified as localized increases in average temperature, while insufficient concrete section or quality can be identified as localized decreases in average temperature. Generally, anomalies present over more than 10% of the effective cross-sectional area are normally seen in multiple thermal wires at the same depth. Areas of soil intrusion or inclusion are indicated by lower local temperatures because soil or slurry pockets, or both, produce lower heat than concrete. The rebar cage location can be estimated based on the relative difference between individual thermal wire temperatures and the average temperature of all wires. Higher individual thermal wire temperatures indicate the wire is closer to the center of the drilled shaft or near a local bulge or increase in diameter, while lower individual thermal wire temperatures indicate the wire is closer to the soil-shaft interface or a local defect. By viewing diametrically opposite thermal wires, instances where a lateral shift of the reinforcing cage has occurred can be determined. If one wire temperature is higher than average and the diametrically opposite wire temperature is lower than the average temperature, cage shifting has probably occurred.

Piscsalko et al. (2016) propose the following drilled shaft acceptance criteria based on TIP temperature results:

- Satisfactory (S):
 - 0% to 6% Effective Average Radius Reduction and Local Cover Criteria Met
- Further Engineering Review Recommended (FE):
 - Effective Average Radius Reduction > 6% or Local Cover Criteria Not Met
 - Two or more adjacent thermal wire cables are missing data; therefore, the calculated Effective Average Radius may be potentially unreliable.

When a tested drilled shaft is categorized as (FE), horizontal slices of the shaft numerically modeled at the depth of question may provide additional clarity so that a structural evaluation of the drilled shaft can be performed by the drilled shaft designer prior to implementing any corrective measures.

CSL Testing

Anomalies in CSL testing are defined as areas that experience an increase in the first arrival time (FAT), a reduction in relative energy of the ultrasonic signal, or a combination of both. As a general guideline, FAT increases of less than 10% are normally considered insignificant. Increases in FAT

between 10% and 30% are usually minor. However, changes in FAT of this magnitude have been verified as defects in a small percentage of cases and not as defects in other cases. FAT increases greater than 30% typically indicate anomalies that should be further evaluated. An increase in FAT is a concern because soil transmits seismic waves slower than intact concrete, so the greater the increase in FAT indicates the greater the amount of soil or the presence of low-strength concrete.

Anomalies in CSL testing can also be defined using reductions in apparent wave speed. Apparent wave speed is defined as the length between the tested access tubes measured at the top of the drilled shaft divided by the FAT. The concrete condition rating criteria (CCRC) is increasingly being used by various state departments of transportation (DOTs) and FHWA as a means of quantifying CSL anomalies based on apparent wave-speed reductions. CCRC is Consultant A's criterion for CSL analysis. FHWA developed a CCRC based on the reduction in V_{p-wave} from 12,000 to 13,000 ft/s (3,660 to 3,965 m/s) (Brown et al., 2018). For example, Table 2 relates the CRCC to the reduction in V_{p-wave} to a quality symbol representing the concrete integrity. Table 2 shows that a decrease in V_{p-wave} of less than 10% corresponds to good quality concrete.

Table 2. Concrete Condition Rating Criteria (CCRC) from FHWA (Brown et al., 2018)

Rating	Symbol	Apparent Wave Speed Reduction	Remarks
Good	G	<10%	Good quality concrete
Questionable	Q	10%–25%	Minor contamination or intrusion and/or questionable concrete quality
Poor/Defect	P/D	>25%	Results indicative of water slurry contamination or soil intrusion and/or poor quality concrete
No Signal	NS	No Signal	Highly probable that a soil intrusion or other severe defect has absorbed the signal
Water	W	C = 4750 to 5000 ft/sec	Indicative of a water intrusion or of water filled gravel intrusion with few or no fines present

CSL was also performed by Consultant A on test drilled shafts #2 and #3 using the Cross-hole Analyzer (CHA) system manufactured by Pile Dynamics, Inc. This differs from test shaft #1, where only Consultant B conducted CSL. This duplicate CSL was undertaken to investigate the repeatability of CSL interpretations.

The CHA system generates electrical signals, which are converted to ultrasonic vibrations by the transmitter probe. These pulses generate sonic waves that travel from the transmitter to the receiver, causing a slight vibration of the receiver. The receiver probe converts this vibration back to an electrical signal. Both the time between pulse generation and signal reception (FAT, for first arrival

time) and the strength of the received signal give a relative measure of the concrete quality between the transmitter and receiver. Alternatively, dividing the distance between transmitter and receiver by FAT value yields an approximate value of the concrete wave speed. The CSL results can be used to evaluate drilled shaft integrity and concrete homogeneity. Drilled shaft integrity may be identified by a consistent FAT between access tubes. Where FAT is delayed, lower quality concrete may be present due to concrete mixing with soil or drilling slurry, honeycombing, or a slower curing rate. A complete loss of signal generally indicates a significant abnormality in the concrete between access tubes due to caving soil or an inclusion within the drilled shaft concrete.

In general, variations in arrival time of 20% are within the normal range for the CSL technique due to variations in probe location within the pipes, pipe alignment, and other factors. The interpretation of Consultant A's CSL testing is dependent on the signal FAT and the signal strength received for each data set collected relative to the average FAT and signal strength. FAT can be visually determined from the left edge of the waterfall diagram. The signal strength is evaluated by digital integration over time of the absolute value of the signal. The duration of the signal integration is typically in the range of 20 to 50 samples (although for longer samples, the shape of the curve usually is similar). The result of this integration is called the "relative energy," which is shown in the left plot as a profile. There are no absolute values of energy that can be used for concrete quality assessment. However, a local relative reduction of "energy" by more than 12 dB usually indicates a serious relative reduction of concrete quality.

The following are Consultant A's proposed categories for classifying the CSL results:

- Class A:
 - Acceptable CSL Test Results: FAT increases less than 15% of the local FAT value AND the reductions in the relative energy are less than 9 dB of the local average value of relative energy.
- Class B:
 - Conditionally Acceptable CSL Test Results: FAT increases are between 15% and 30% of the local average FAT value AND the reductions in the relative energy are less than 12 dB of the local average value of relative energy.
 - OR
 - FAT increases are less than 15% of the local FAT value AND the reductions in the relative energy are greater than 9 dB of the local average value of the relative energy.
- Class C:
 - Highly Abnormal CSL Test Results: FAT increases greater than 30% of the local average FAT value.
 - OR
 - FAT increases are greater than 15% of the local FAT value AND the reductions in the relative energy are greater than 12 dB of the local average value of relative energy.

CHAPTER 3: COST ANALYSIS

This chapter is a summary of the cost analysis shown in Appendix B. Cost analysis and comparison between the cost of CSL and TIP testing is important for developing recommendations for selecting nondestructive tests for drilled shafts in Illinois. These data are used to evaluate the cost effectiveness of each test method along with their advantages and disadvantages in order to assess whether the additional advantages of one method are worth the additional investment. A comprehensive cost analysis was conducted for TIP and CSL testing using historical projects that were provided by IDOT. IDOT provided the research team with 7 TIP testing contracts and 28 CSL testing contracts. The 7 TIP projects were awarded using the new (after 2016) IDOT pricing method, 14 of the CSL projects were awarded using the old (2016 and earlier) IDOT pricing method, and the other 14 CSL projects were awarded using the new (after 2016) IDOT pricing method. In the old IDOT pricing method, there was only one pay item for CSL testing, which includes the cost of the access ducts, conducting the tests, analyzing the data, and compiling a testing and recommendation report. In these projects, all drilled shafts in a project had CSL access tubes installed but only a few of these drilled shafts were tested and analyzed. In the new IDOT pricing method for CSL, there is one pay item for installation of access ducts and another pay item for testing, analysis, and preparation of a report. In the IDOT pricing method for TIP, there is one pay item for installation of the thermal wires and collection of the data and a second pay item for data analysis and report preparation.

The cost analysis of TIP and CSL testing is complex because of the different pricing methods and factors affecting the cost of each method. Some factors affecting the cost of TIP and CSL testing include the volume of tested drilled shafts, number of drilled shafts tested, different contractors, project locations, and total drilled shaft volume in a project. Total drilled shaft volume includes the non-tested drilled shafts, because even the non-tested drilled shafts have access tubes or TIP wires installed in them, or both. Furthermore, most of this information is either not known, not collected, or would have made the comparison more complicated.

Therefore, the researchers decided to limit the comparison between TIP and CSL testing to two parameters as shown below and detailed in Appendix B:

1. Comparison 1: Between the average volume of one tested drilled shaft and the average cost of integrity testing for one tested drilled shaft
2. Comparison 2: Between the average volume of one tested drilled shaft and the average cost per cubic yard of concrete of tested drilled shaft

These two comparisons were chosen to present a cost overview for IDOT and potentially other engineers that will facilitate estimating future costs for TIP and CSL testing. Figure 1 shows the average cost of CSL and TIP testing for one tested drilled shaft, and the general trend is the cost increases with increasing average volume of one tested drilled shaft. Conversely, Figure 2 presents the average cost of one cubic yard of tested drilled shaft and the unit cost of CSL and TIP testing per cubic yard decreases with increasing average volume of one tested drilled shaft.

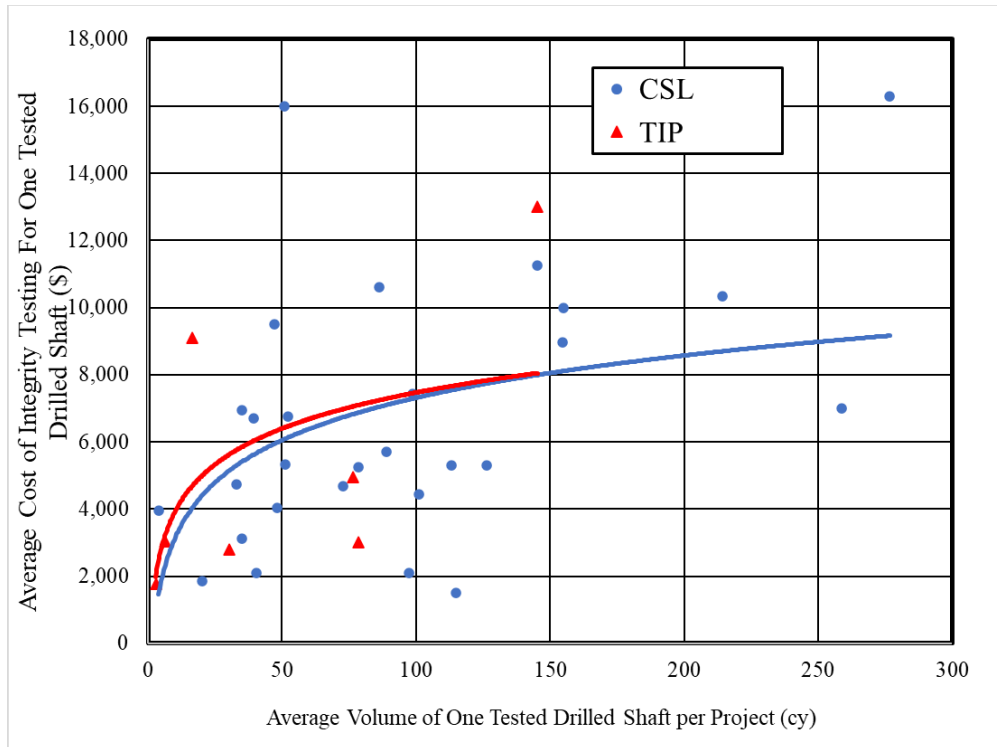


Figure 1. Graph. TIP and CSL costs per one tested shaft versus average volume of one tested drilled shaft per project.

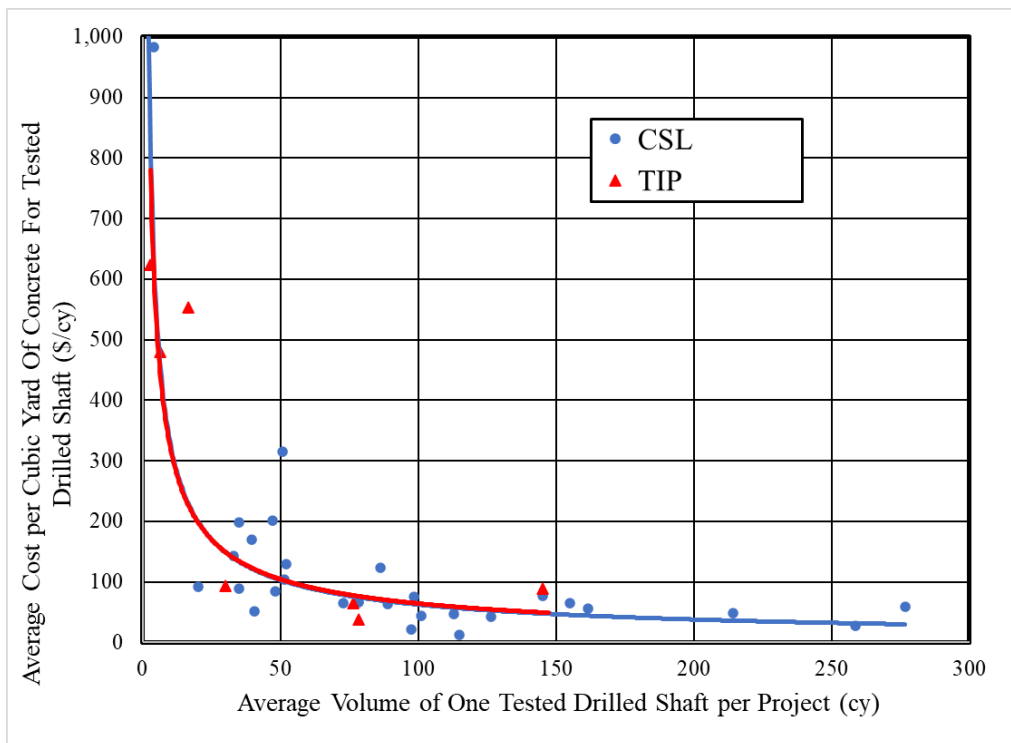


Figure 2. Graph. TIP and CSL costs per cubic yard of a tested shaft versus average volume of one tested drilled shaft per project including only IDOT data.

Based on the data in Figure 1 and Figure 2, the costs of TIP and CSL testing are comparable, but there are case-by-case differences. The figures and bar charts shown in Appendix B may be helpful for IDOT and other states to develop a general idea of cost when selecting integrity tests based on the project volume, drilled shaft volume, and total average drilled shaft cost. However, this comparison is based on a limited number of IDOT TIP testing projects (only 7) compared to 28 IDOT CSL projects.

CHAPTER 4: TEST DRILLED SHAFT #1

This project involved constructing three drilled shafts with pre-planned defects in certain places and then conducting TIP and CSL testing as well as concrete coring to evaluate which nondestructive test method better detected certain types of defects. For test drilled shaft #1, SHAPE and SQUID testing were also performed as was suggested by the consultant (Consultant A). Unfortunately, SHAPE and SQUID testing were not performed on test drilled shafts #2 and #3 because they did not provide additional detection of the installed defects. The location of test drilled shaft #1 is shown in Figure 50 of Appendix C.

INTRODUCTION

A detailed longitudinal profile of the initial design of test drilled shaft #1 is shown in Figure 3. Test drilled shaft #1 is in the highway median along I-72 in Macon County near Decatur, Illinois. In particular, Figure 3 shows the design of the drilled shaft with details of the temporary casing used, shaft diameter, and length. Figure 3 also shows the planned defects included in the test drilled shaft, which include a soft toe and various concrete placement delays and tremie pipe raises. The main design parameters for test drilled shaft #1 are a length of 50 ft, shaft diameter of 4 ft, rebar cage length and diameter of 53 ft and 3.5 ft, respectively, and a 4.5 ft diameter temporary casing to a depth of 5 ft. The test drilled shaft rebar cage was designed to be 50 ft below ground surface and 3.5 ft above ground surface to facilitate instrumentation.

TEST DRILLED SHAFT #1 CONSTRUCTION

Fabricated plastic centralizers were installed on only one side of the rebar cage (see left side of the rebar cage in Figure 3) every 3 ft, starting from the ground surface to a depth of 24 ft with an 8 in. diameter for the first two vertical centralizers that are inside the temporary casing and a 5 in. diameter for the rest of the centralizers outside the temporary casing. These centralizers were installed to create a shifted rebar cage to determine the effectiveness of TIP and CSL testing in identifying this defect. Based on the 8 in. and 5 in. centralizers, the rebar cage was shifted by 4 in. from depths of 2 to 12 ft and by 2.5 in. from depths of 15 to 25 ft. A soft toe was created at the bottom of the drilled shaft at a depth of 50 ft. A soft toe means the bottom of the drilled shaft was not cleaned out so soil or cuttings, or both, were left at the tip of the shaft. Approximately 6 in. of soil was left at the tip of the shaft to assess the effectiveness of TIP and CSL testing in detecting this common condition.

Concrete was poured using the wet method for test shaft #1. The following concrete placement variables were added to the construction process: a 2 ft tremie raise at a depth of 41 ft depth, a two-hour concrete delay at a depth of 30.7 ft, and a 4 ft tremie raise at a depth of 11.4 ft. The two-hour concrete delay occurred after the second concrete truck finished unloading to reflect a delay in the arrival of the third truck. During this two-hour delay, the tremie pipe was pulled out of the shaft before resuming concrete pouring.

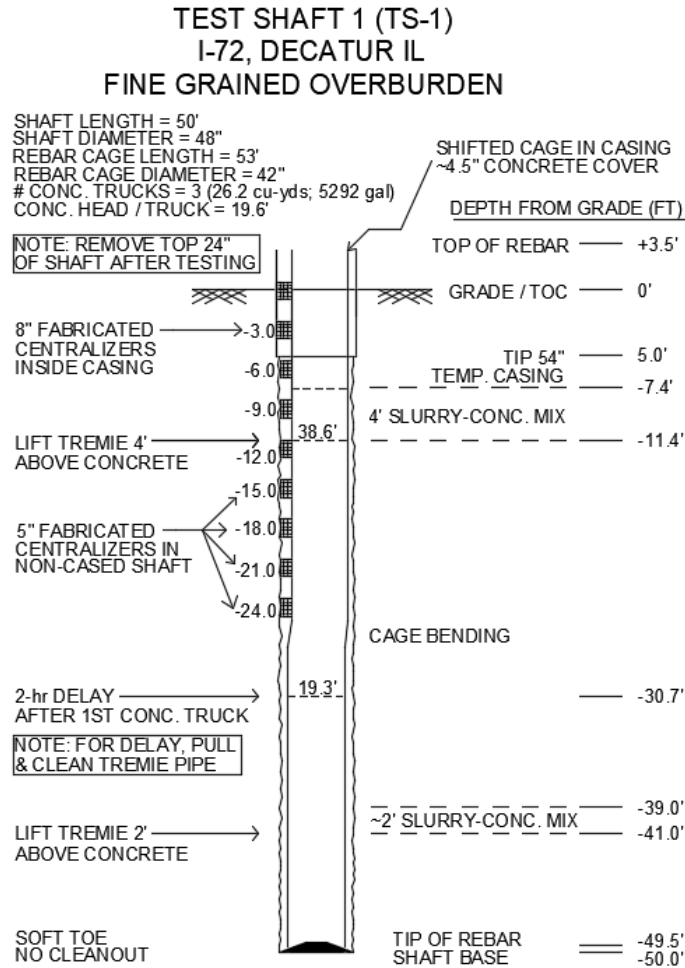


Figure 3. Illustration. Initial design of test drilled shaft #1 near Decatur, Illinois (along I-72).

Figure 4 shows the design cross section of test drilled shaft #1, where the details of the rebar cage are shown. The outside diameter of the rebar cage is 3.5 ft with a 7 in. clear distance between the longitudinal rebars, which are 16 #8 vertical rebars and #6 hoops at 12 in. vertical spacing. Figure 4 also shows the four CSL steel access tubes installed inside the rebar cage (one per foot of shaft diameter), each with a 2 in. outside diameter.

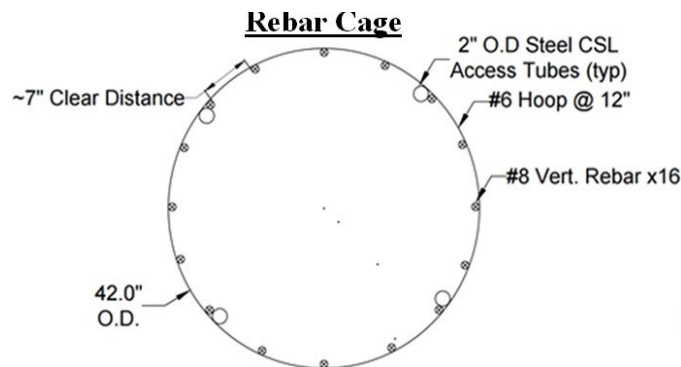


Figure 4. Illustration. Initial design cross section of test shaft #1 with reinforcement detail.

Test drilled shaft #1 was poured on September 23, 2019, using the wet method, with water being present from the groundwater at a depth of 28 ft and additional water being added to the shaft before concrete pouring. The concrete was placed via a pump truck and tremie pipe. The elevation of the ground surface was 688.5 ft at the time of construction. The drilled shaft has a 4.5 ft diameter by 8.5 ft long temporary casing extending 7 ft below the ground surface instead of 5 ft as was in the original design. The reported placed concrete volume is 30 cubic yards. Drilled shaft information, soil boring logs, and installation details are shown in Appendix C. The cage was instrumented with four thermal wire cables, one per foot of shaft diameter, extending to the bottom of the cage. The wires were numbered clockwise, with wire 1 corresponding to the wire in the northeast position. The reinforcing cage measured 3.5 ft in diameter with an overall length of 53 ft. The total drilled shaft length is 50 ft below ground surface.

Figure 5(a) shows the 3.5 ft diameter rebar cage with 4 CSL access tubes and 4 TIP thermal wires already installed before placement in the drilled shaft. Figure 5(b) shows the 3.5 ft diameter rebar cage with 4 CSL access tubes and 4 TIP thermal wires after concrete pouring.

Figure 6 shows the as-built detail of test drilled shaft #1 after construction. The actual length of casing below the ground surface is 7 ft, the soft toe is 6.4 ft, the first tremie raise of 3.2 ft occurred at 33 ft, and the second tremie raise of 1.5 ft occurred at 9 ft. After the second concrete truck finished pouring concrete, the depth to concrete was 29.0 ft. After a delay of two hours between the second and third concrete truck, the depth to concrete decreased to 28.3 ft before starting to pour the third truck of concrete. This 0.7 ft increase in the top of the concrete level could be attributed to a difference in measurement location of the tape. This would occur by not measuring from the same location on the casing after the two-hour delay.



(a)



(b)

Figure 5. Photo. Photographs showing (a) 3.5 ft diameter rebar cage with 4 CSL access tubes and 4 TIP thermal wires installed before placement in shaft and (b) installed rebar cage after concrete pouring and connection of TIP readout boxes.

**AS-BUILT
TEST SHAFT 1 (TS-1)
I-72, DECATUR IL
FINE GRAINED OVERBURDEN**

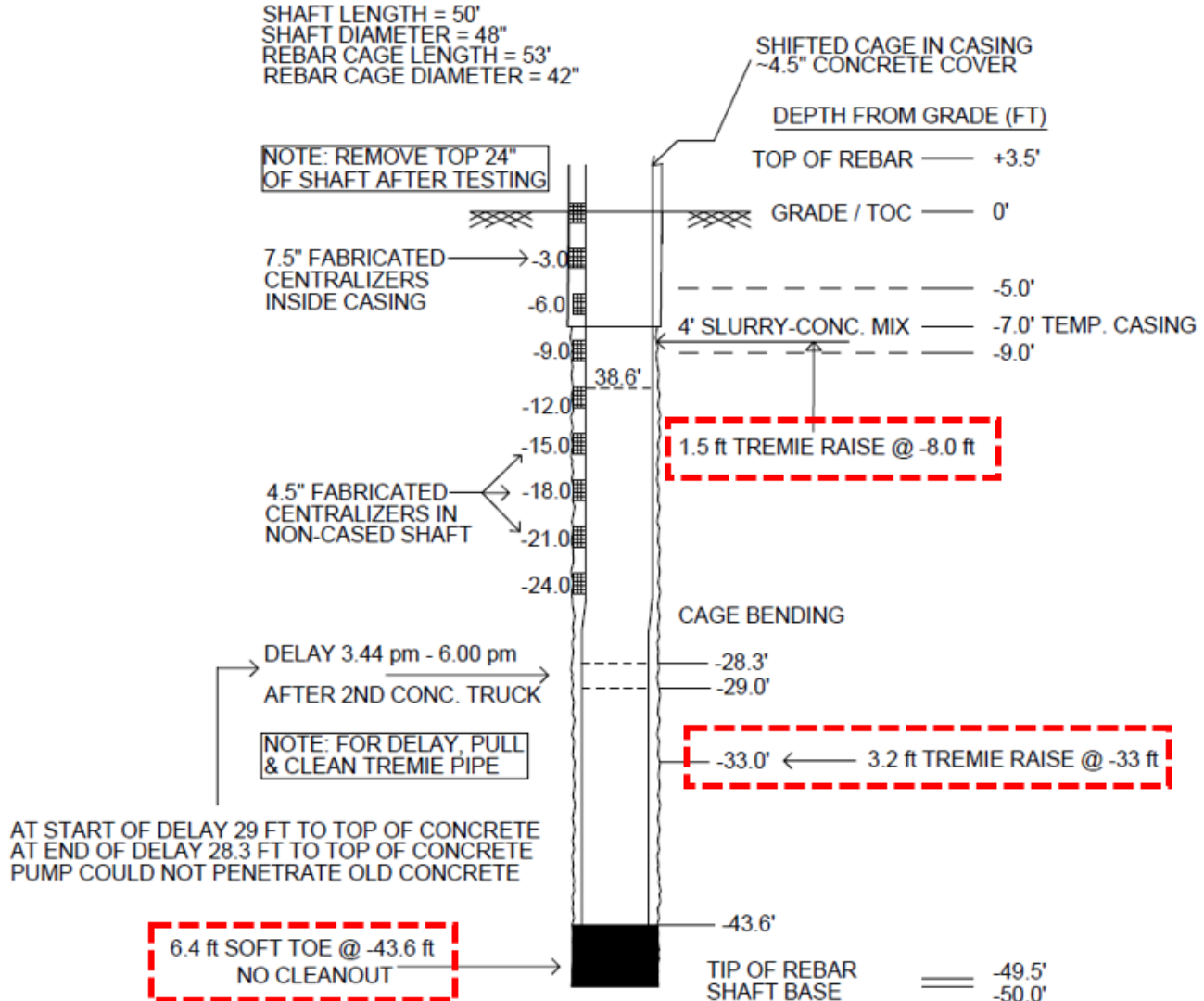


Figure 6. Illustration. As-built diagram for test drilled shaft #1.

TIP TESTING

Temperature at Rebar Cage for Ideal Shaft

Unfortunately, it is difficult to estimate the temperature profile of an ideal drilled shaft at the rebar cage because during construction there is no ideal drilled shaft. As a result, the temperature profile of an ideal drilled shaft at the rebar cage must be estimated or numerically estimated. There are few studies that have tried to estimate this temperature by modeling the concrete drilled shaft temperature, which conflict with each other. Therefore, in this report, Consultant A's evaluation

method of the TIP testing data will be adopted for evaluating the integrity of test drilled shaft #1. However, ongoing research is investigating the most reliable method for evaluating TIP data. This research may lead to a more reliable method for evaluating temperature profiles from TIP testing data to evaluate drilled shaft integrity. Appendix C shows further discussion and procedures to obtain the temperature profile at the rebar cage of an ideal shaft.

Consultant A's Results

Test drilled shaft #1 achieved peak temperature approximately 29 hours after completion of concrete placement. The optimal time selected for the drilled shaft analysis usually occurs between one-half the time to peak temperature and peak temperature. When anomalies are indicated in the thermal data, the analyses are normally performed closer to one-half the time to peak temperature peak temperature, when the temperature differences have greater contrast. Consultant A analyzed the data at 19.5 hours after concrete placement. Consultant A's analysis of the TIP data identified the following three areas of concern: (1) a depth of 32 ft, (2) a depth of 28 ft, and (3) the bottom of the drilled shaft. The temperature reduction at a depth of 32 ft is more prominent than the reduction at 28 ft, but in both cases the magnitude of the reduction appears minimal relative to the oversized effective radius within this portion of the drilled shaft. The reduction at the bottom of the drilled shaft is identified as a defect. Further discussion of Consultant A's analysis is shown in Appendix C.

UIUC's Interpretation of TIP Results

An interpretation of the measured temperature profiles with depth for all thermal wires was also conducted by the research team at the University of Illinois Urbana-Champaign (UIUC). The temperature profiles at the peak, and one-half the time to peak temperatures are considered in the analysis described below. Boeckmann and Loehr (2018) show that the analysis of TIP data is more sensitive to defects at times corresponding to roughly one-half the time to peak temperature and yields more accurate assessment of potential defects. Figure 7 presents the temperature versus depth profile for the four thermal wires in test drilled shaft #1 at peak temperature and one-half the time to peak temperature.

The measured profiles indicate a reduction in temperature in all thermal wires starting at a depth of 7 ft. This depth corresponds to the first planned defect, which is a 1.5 ft high tremie pipe raise at a depth of 8 ft. This temperature reduction is probably due to changing the diameter of the drilled shaft from the cased diameter of 4.5 ft to the uncased diameter of 4 ft and the tremie raise at 8 ft. This conclusion is based on the temperature reduction not being an abrupt reduction at one specific location but the reduction starting at 7 ft and continuing to reduce gradually with depth. However, there is a sharp temperature reduction in wires #1 and #4 at a depth of 10 ft at one-half the time to peak temperature and peak temperatures data figures, and therefore, the detection of the 1.5 ft tremie raise at 8 ft is inconclusive. The 4 in. offset of the rebar cage from 2 to 12 ft can be observed in one-half the time to peak temperature (see Figure 7[a]) to peak (see Figure 7[b]) data. For example, wire #4 shows a temperature higher than wire #1 up to a depth of 12 ft, after which wire #1 shows a higher temperature than wire #4.

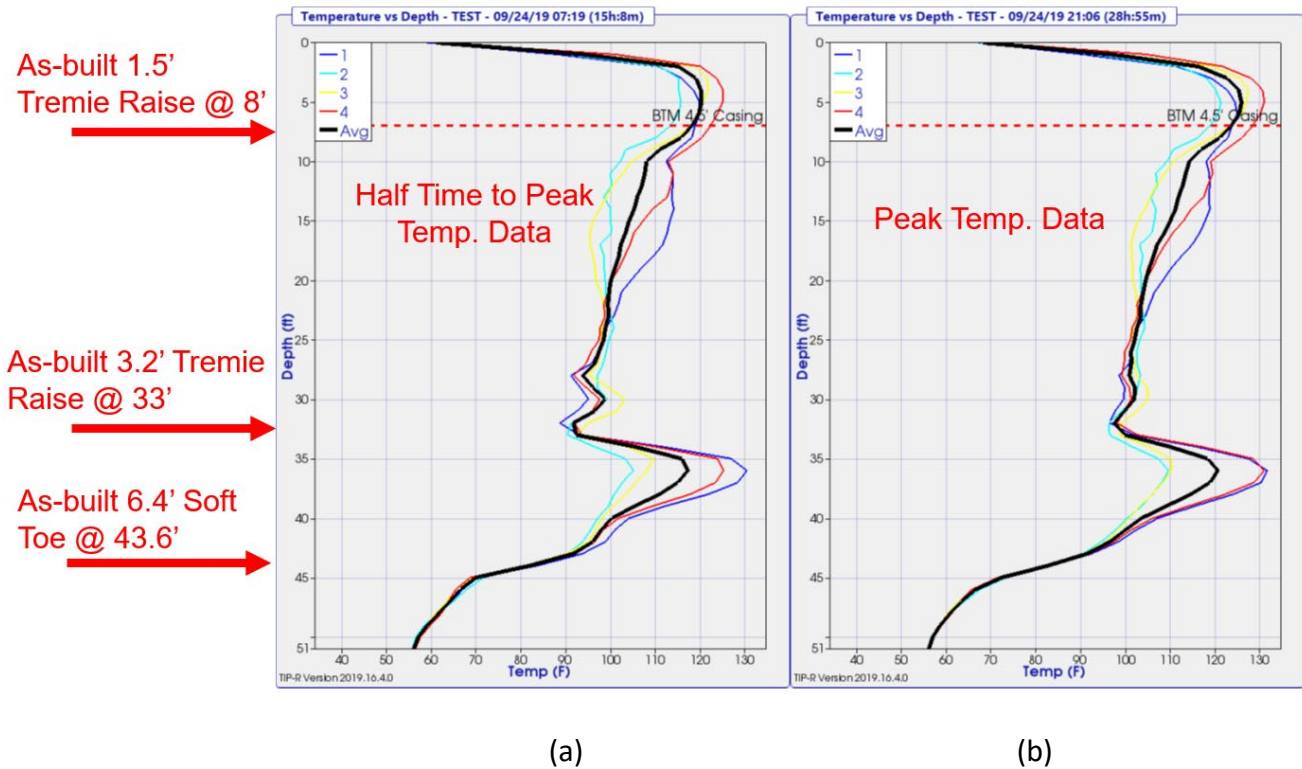


Figure 7. Graph. Temperature versus depth profiles for four thermal wires in test shaft #1: (a) at one-half time to peak temperature and (b) at peak temperature, with red arrows showing the location of installed defects.

The second rebar cage shift of 2.5 in. from depths of 15 to 25 ft can be observed in the one-half the time to peak temperature and peak temperature data between all wires. For example, above a depth of 25 ft, wires #1 and #4 had higher temperatures than wires #2 and 3 but right below a depth of 25 ft, wires #1 and #4 had lower temperatures than wires #2 and #3. Figure 7(a) shows there is a clear reduction in all temperature profiles from depths of 28 to 32 ft, which is more pronounced in the one-half time to peak temperature profiles (see Figure 7[a]) than in the peak temperature profile (see Figure 7[b]). These two temperature reductions correspond to the two defects installed at that location: a cold joint between 28.3 to 29 ft and a 3.2 ft tremie pipe raise at a depth of 33 ft.

The 6.4 ft soft toe is also observed in Figure 7, where the reduction in temperature is large and does not correspond to only a temperature decrease due to the lower ground temperature. The normal reduction in temperature near the bottom of the drilled shaft due to the lower ground temperature is referred to as “temperature roll-off.” A similar “roll-off” is visible at the top of the shaft due to the lower ambient temperature. As a result, a “temperature roll-off” is usually visible at the top and bottom of the instrumented drilled shaft. Table 3 shows a summary of the installed defects along with the interpretations developed by Consultant A and UIUC researchers based on the TIP temperature data.

Table 3. Summary of TIP Data Interpretation by Consultant A and UIUC for Test Drilled Shaft #1

Defect	Consultant A Interpretation	UIUC Interpretation
Shaft diameter change at 7 ft	Detected oversized diameter to bottom of casing at ~7 ft	Detected well
4 in. offset cage at 2 to 12 ft	Not detected due to oversized diameter	Detected via wire #4 and dissipates at wire #1
1.5 ft tremie raise at ~8 ft	Not detected	Inconclusive
2.5 in. offset cage ~15 to 25 ft	Inconclusive	Detected via all wires
2.25 hours cold joint at ~29.0 ft at the beginning of delay and 28.3 ft after concrete resumed	Possibly reduced diameter ~28 ft	Detected well
3.2 ft tremie raise at ~ 33 ft	Possibly reduced diameter ~32 ft	Detected well
44 to 50 ft soft toe (6.4 ft deep)	Below 45 ft is zero heat—detected well	Detected well

CSL TESTING

Consultant B performed crosshole sonic logging (CSL) in test drilled shaft #1. CSL was performed in accordance with ASTM D6760 (2016) using the cross-hole ultrasonic module manufactured by Piletest. Test drilled shaft #1 had concrete placement on September 23, 2019, and the CSL testing was performed eight days later on October 1, 2019. Test drilled shaft #1 contains four access tubes for CSL testing. The access tubes consist of 2 in. diameter steel pipes in 10 ft lengths threaded together. Appendix C presents the access tube arrangement for test shaft #1. Initial CSL testing was performed on six combinations of access tubes. CSL measurements were taken along the length of the access tubes at 1 in. increment depth intervals. The average height of steel access tube stickup above the top of concrete is approximately 2.7 ft at the time of CSL testing. The average steel access tube bottom elevation for the drilled shaft is 639.1 ft of a depth below ground surface of 50 ft. Based on the available data, the drilled shaft bottom elevation is at approximately 638.5 ft. The distance between the average bottom elevation of the access tubes and the estimated bottom elevation for the drilled shaft is approximately 0.6 ft. Elevation summaries of the CSL access tubes for test drilled shaft #1, referenced from the top of shaft (TOS) elevation of 688.5 ft, are provided in Table 4.

Table 4. Access Tube Summary at Time of CSL Testing

Access Tube	TOAT ¹ Elevation (ft)	Tube Stickup ² (ft)	BOAT ³ Elevation (ft)
1	691.3	2.8	638.8
2	691.3	2.8	639.0
3	691.0	2.5	639.1
4	691.3	2.8	639.4
Average	691.2	2.7	639.1

Notes:

1. TOAT = Top of access tube

2. Tube Stickup = Difference between top of access tube and top of drilled shaft concrete

3. BOAT = Bottom of access tube

A review of the drilled shaft installation logs in Appendix C for test drilled shaft #1 revealed the following observations:

- No significant deficiencies or irregularities were observed during concrete placement.
- An apparent concrete volume difference of 5.2 cubic yards (yd³) was observed between apparent volume of concrete placed (29.3 yd³) and theoretical concrete volume (24.1 yd³). This is an apparent concrete over-pour of approximately 21%, which is typically considered excessive. The theoretical concrete volume was determined from the various drilled shaft diameters and lengths provided and is based on an assumed bottom of shaft (BOS) elevation of 638.5 ft and a TOS elevation of 688.5 ft, i.e., a length of 50 ft. One explanation is the apparent volume of concrete placed includes excess concrete that is pumped until it flows over the top of the casing as well as subtracting concrete that is left in the truck. It is sometimes difficult to quantify these amounts and should be considered an estimate only because the results may affect the amount of concrete over-pour calculated.

Consultant B's Results

In general, Consultant B's interpretation of the CSL test results for test drilled shaft #1 show only minor deviations in FAT and relative energy in the tested tube combinations along the length of the drilled shaft. These minor fluctuations are less than 10% and, therefore, can be considered insignificant. An example of the CSL testing FAT and relative energy plots with depth for different combinations of access tubes are shown in Figure 8, Figure 9, and Figure 10. These figures show the relative energy with FAT for different combinations between different tubes, where a sketch of the tube configuration is shown at the top of FAT and relative energy profiles. Figure 8(a) shows the FAT and relative energy profiles between access tubes 1–2, and Figure 8(b) shows the same profiles between access tubes 1–3, which is across the shaft diameter. Figure 9(a) shows the FAT and relative energy profiles between CSL tubes 1–4 and between CSL tubes 2–3 in Figure 9(b). Finally, Figure 10(a) shows the FAT and relative energy profiles between CSL tubes 2–4, which is across the shaft diameter and Figure 10(b) between CSL tubes 3–4.

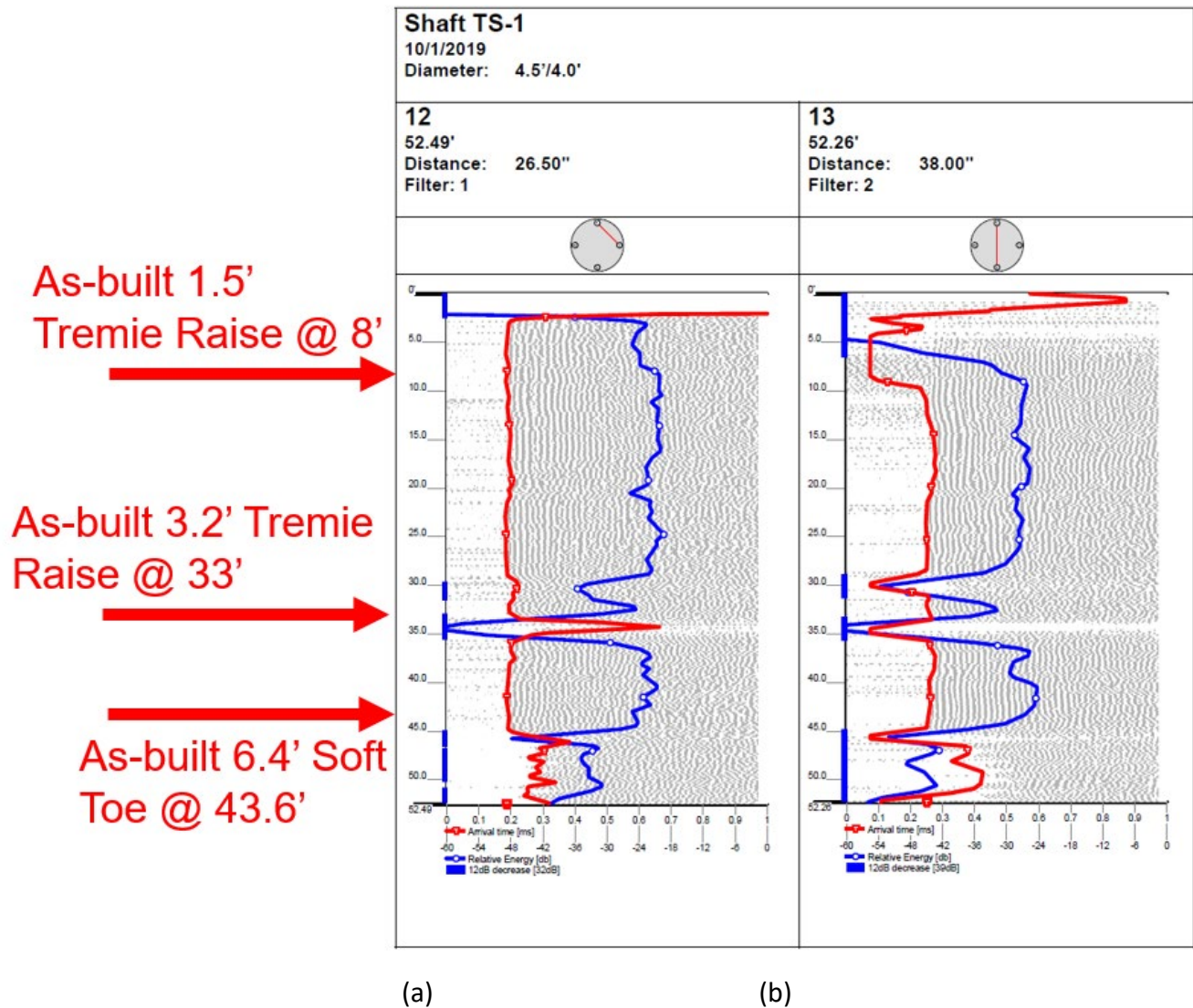


Figure 8. Graph. Consultant B's CSL results for test drilled shaft #1 for (a) along an edge of the shaft (profile 1-2) and (b) across the shaft (profile 1-3), with red arrows showing defect locations.

Figure 8 show the CSL results for test drilled shaft #1 with the defect locations indicated with red arrows to facilitate interpretation of the test results.

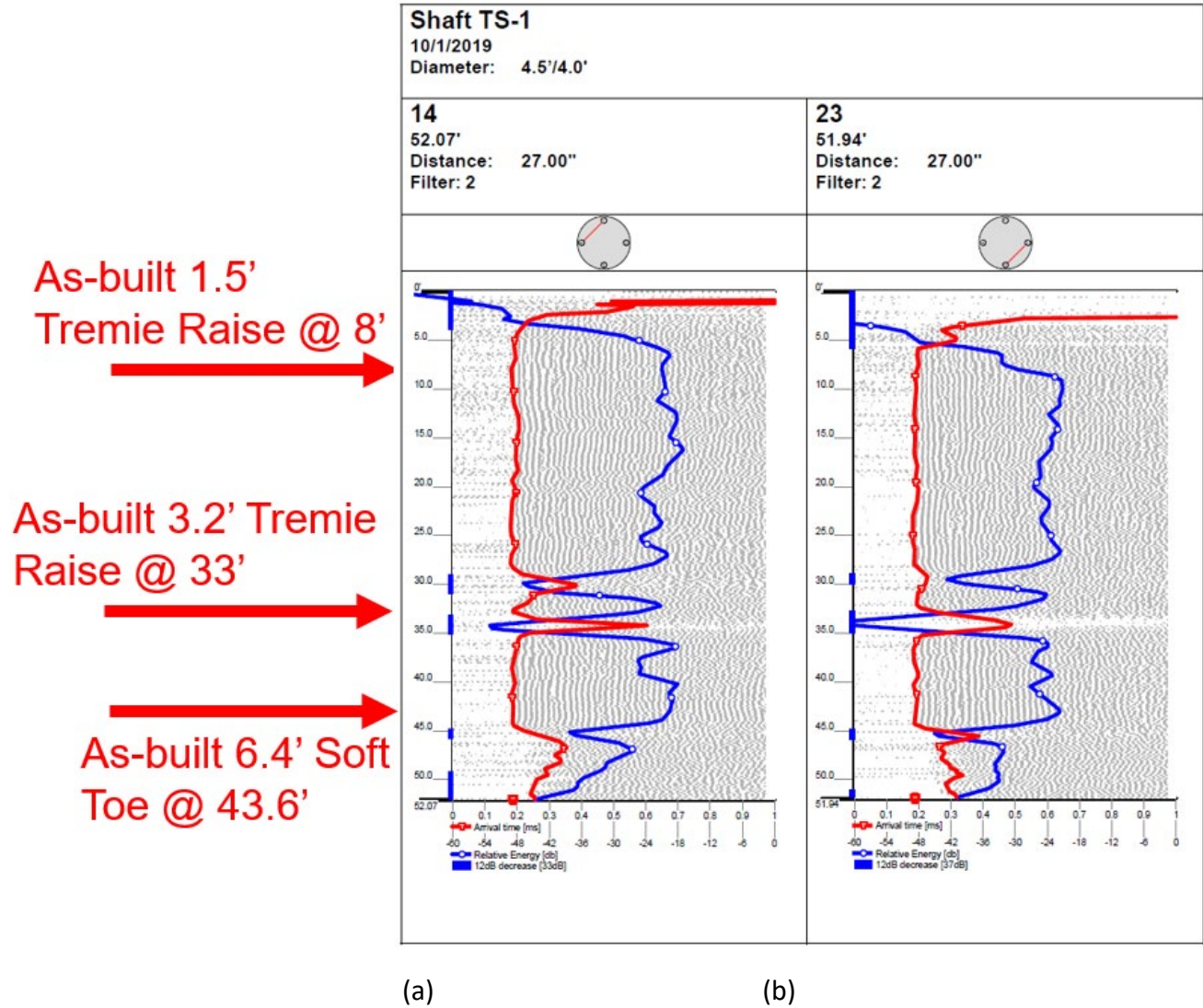


Figure 9. Graph. Consultant B's CSL results for test drilled shaft #1 along edges of the shaft: (a) profile 1-4 and (b) profile 2-3, with red arrows showing defect locations.

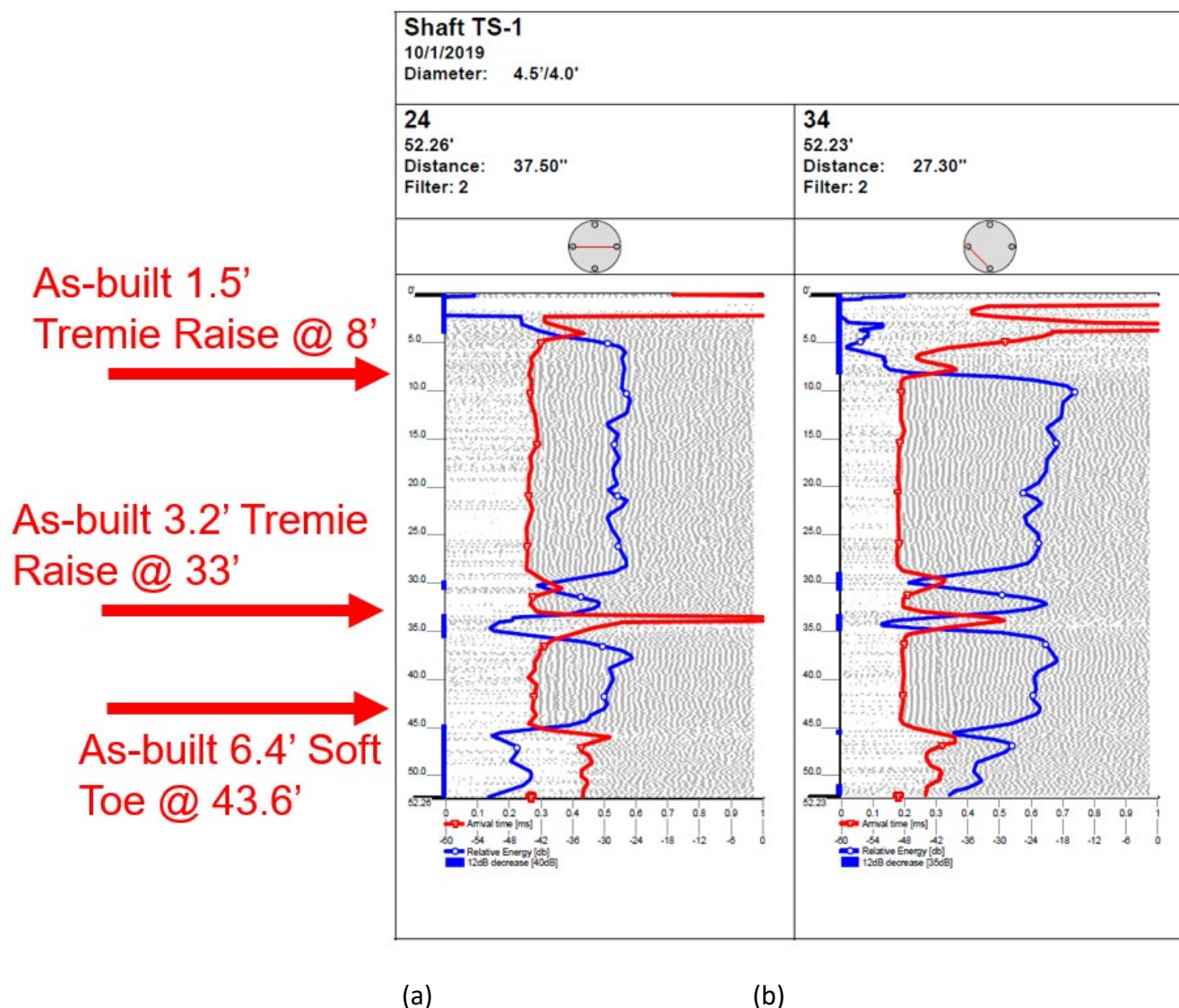


Figure 10. Graph. Consultant B's CSL results for test drilled shaft #1 for (a) across the shaft (profile 2–4) and (b) along the edge of the shaft (profile 3–4), with red arrows showing defect locations.

A review of these figures shows there are two zones of increased FAT and decreased relative energy within all six tested access tube combinations from the BOS to an average depth of 45 ft (Anomaly Zone A) and between an average depth of 36 ft and 30 ft (Anomaly Zone B). Anomaly Zones A and B correspond to elevations of 638.5 to 643.5 ft and 652.5 to 658.5 ft, respectively. The CSL test results within these two zones correspond to a CCRC rating of Poor/Defect (P/D). The estimated extent of the anomaly zones, determined from the test access tube data, covers approximately 12.5 ft² (about 100%) of the drilled shaft area at each depth or elevation range. In addition to the deeper anomalies, there is a zone of increased FAT and decreased relative energy observed within three of the tested access tube combinations, ranging from the TOS to an average depth of 3 ft below TOS (Anomaly Zone C). This corresponds to elevations of 688.5 to 685.5 ft. The CSL test results within this zone also correspond to a CCRC rating of Poor/Defect (P/D). Anomaly Zone C could indicate debonding of the

tubes at the top 3 ft of the shaft as testing was performed eight days after concrete pouring which is slightly more than the recommended CSL testing time of 3 to 7 days.

Concrete apparent wave speeds were calculated for each tested access tube combination using the values of FAT within intact concrete in the upper 10 ft, access tube distances at the TOS measured at the time of CSL testing, and the procedure to account for access tube effects discussed by Amir et al. (2004). The calculated apparent wave speeds range from 12,100 to 13,400 ft/sec, with an average value of 12,770 ft/sec (± 435 ft/sec). The standard deviation in apparent wave speed between the tested access tube combinations of 3% is indicative of uniform concrete. A summary of the calculated concrete apparent wave speeds is presented in Table 5.

Table 5. CSL Testing Apparent Wave Speed Summary

Access Tube Combination	Apparent Wavespeed¹ (ft/sec)
1–2	12,500
1–3	13,200
1–4	12,800
2–3	12,600
2–4	12,100
3–4	13,400
Average	12,770
Std. Dev.	435
Minimum	12,100
Maximum	13,400

Note: 1. Apparent wave speed calculated within the upper 10 ft of the drilled shaft.

A comparison was conducted by Consultant B between the calculated concrete apparent wave speeds in the access tube combinations and several published guidelines for relating concrete quality with compression wave velocities (e.g., Malhotra, 1976; Harrell & Stokoe, 1984; Ferraro, 2003; Deep Foundations Institute, 2005). This comparison is presented in Figure 11 and shows the calculated concrete apparent wave speed is within the “Good” concrete range for the majority of the published guidelines. Even under tight control, concrete properties will show scatter that can have a material influence on the results of CSL testing (Amir et al., 2004). Therefore, CSL test results can indicate significant changes in concrete quality, but if more accurate verifications of the actual compression strength is needed, the compressive strength tests from sample cylinders or concrete cores will be needed.

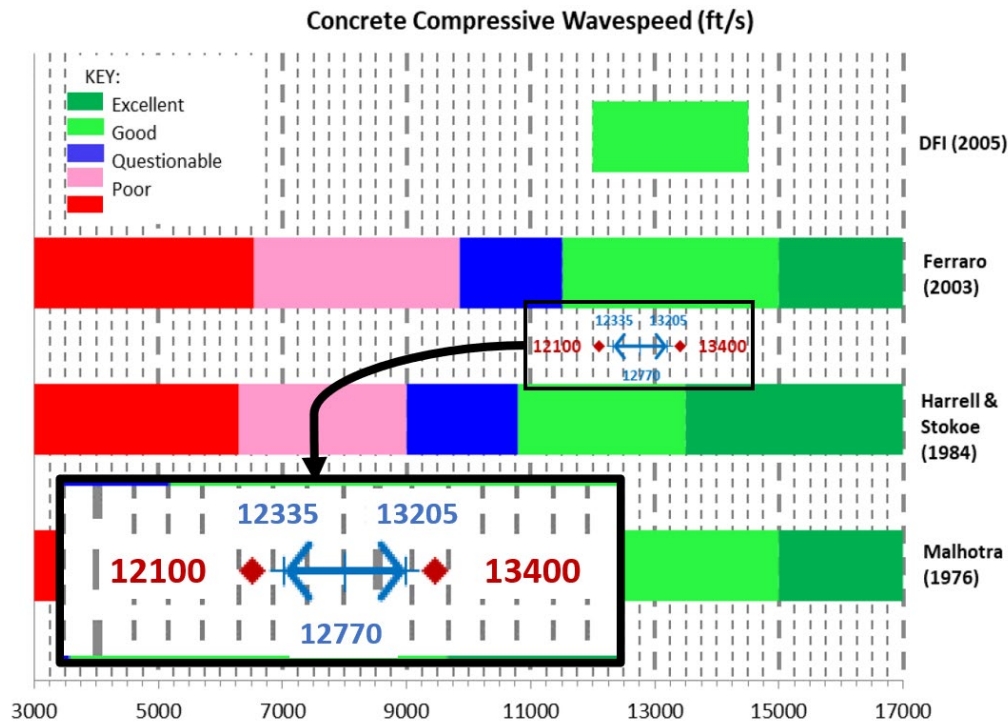


Figure 11. Chart. Calculated concrete wave speed comparisons.

Based on Consultant B’s CSL testing and analysis and their review of available drilled shaft installation records, test drilled shaft #1 contains at least three anomalies, outlined below. Consultant B bases this conclusion on the following observations:

- Increased values of FAT and decreased relative energy were observed in all six of the tested access tube combinations within Anomaly Zones A and B. The CCRC rating in Anomaly Zones A and B is Poor/Defect (P/D).
- Increased values of FAT and decreased relative energy were observed in three of the six tested access tube combinations within Anomaly Zone C. The CCRC rating for Anomaly Zone C is Poor/Defect (P/D). However, this zone appears to only include access tube 3 and only in a zone within the upper 3 ft of the drilled shaft. This anomaly is likely related to tube debonding at the top of the drilled shaft for access tube 3 only.
- No significant anomalies were observed in the remainder of the drilled shaft based on the CSL test results.
- Overall, test drilled shaft #1 has an average concrete quality rating of “Good,” as determined using the average apparent wave speed calculations near the drilled shaft top from CSL data.

UIUC’s Interpretation of CSL Results

Figure 8, Figure 9, and Figure 10 show the CSL testing performed on test drilled shaft #1 and used by the research team to assess the integrity of this shaft. The three figures show a clear reduction in

relative energy (see the blue line in Figure 8, Figure 9, and Figure 10) from ground surface to 3 to 6 ft, around 30 ft, around 35 ft, and from 45 ft to the shaft bottom. The FAT profiles also show an increase in FAT in the same locations where a decrease in relative energy was observed in all figures. In addition to the FAT increase shown in profiles 1–3 in Figure 8, there is also a decrease in FAT that is observed from 2 to 9 ft, around 30 ft, around 35 ft, around 45 ft, and at the bottom of the drilled shaft. The defect observed around a depth of 30 ft corresponds to the cold joint at 29 ft, the defect observed around 35 ft corresponds to the 3.2 ft tremie pipe raise at 33 ft, and the last defect observed from 45 ft to the bottom of the drilled shaft corresponds to the 6.4 ft soft toe.

For the bottom of the temporary casing at 7 ft, Figure 8, Figure 9, and Figure 10 do not show clear evidence of a defect or a change in diameter. These figures only show reduction in relative energy and increase in FAT from the ground surface to a depth of 3 to 6 ft, which is not expected to be caused by the change in diameter at the end of casing at a depth of 7 ft. This is because few profiles show the defect up to 7 ft, and a change in diameter would not be shown as a defect from the ground surface, but as an abrupt change at 7 ft. CSL can only detect the defects between the access tubes, and therefore, is not expected to observe the change in shaft diameter due to the larger casing near the ground surface. This is the same reason why the two cage shifts are not observed by CSL data between 2 and 12 ft and between 15 and 25 ft.

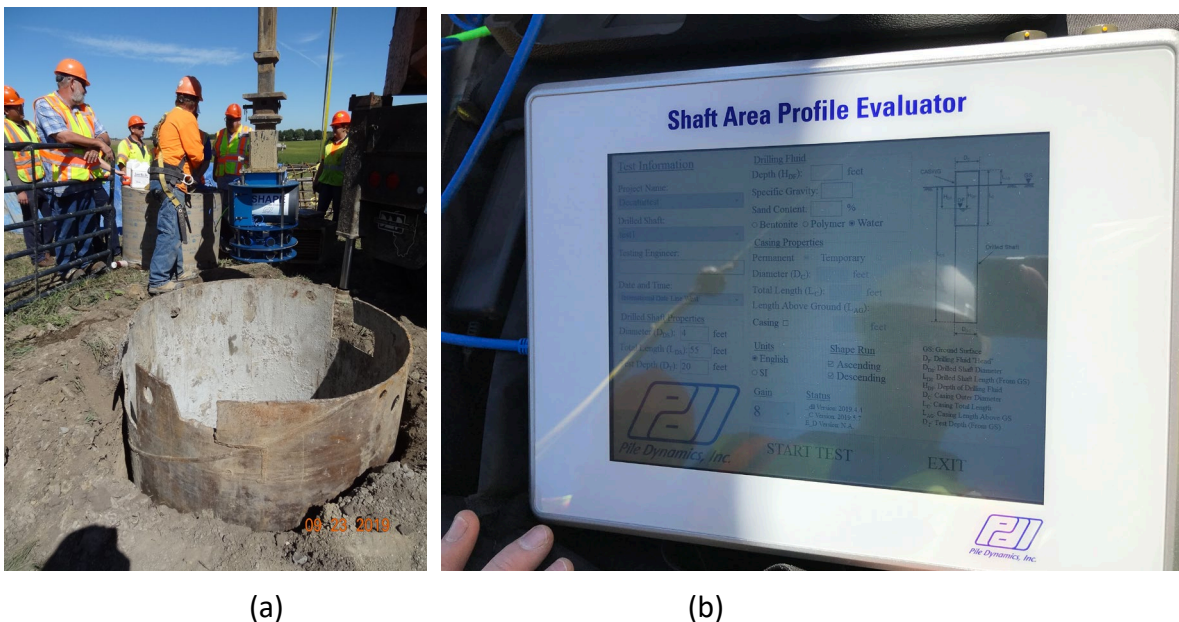
The 1.5 ft tremie pipe raise at 8 ft was also not detected by CSL, as no reduction in relative energy or increase in FAT is observed at 8 ft by any of the profiles shown in Figure 8, Figure 9, and Figure 10. Table 6 shows a summary of the installed defects along with Consultant B's and UIUC's interpretation of the CSL results and data.

Table 6. Summary of CSL Interpretation by Consultant B and UIUC for Test Drilled Shaft #1

Defect	Consultant B Interpretation	UIUC Interpretation
Shaft diameter change at 7 ft	Detected poor concrete to depth of 3 ft	Detected poor concrete from 3 to 6 ft
4 in. offset cage at 2 to 12 ft	Not detected	Not detected (outside cage)
1.5 ft tremie raise at ~8 ft	Not detected	Not detected (outside cage)
2.5 in. offset cage ~15 to 25 ft	Not detected	Not detected (outside cage)
2.25 hours cold joint at ~29.0 ft at the beginning of delay and 28.3 ft after concrete resumed	Detected	Detected around 30 ft
3.2 ft tremie raise at ~33 ft	Detected	Detected around 35 ft
44 to 50 ft soft toe (6.4 ft deep)	Detected well	Detected

SHAPE Testing

SHAPE is the shaft area profile evaluator developed by Consultant A. SHAPE has eight ultrasonic signals that scan the sides of an excavation, providing a quick and economical view of the drilled shaft vertically and the radius, shape, and drilled hole volume, prior to concrete placement in wet conditions. Advancement rate of the drilling stem with the SHAPE attached is approximately one foot per second, offering 360° and 2D and 3D profile views from the results. SHAPE software generates a report based on the data collected during testing. The software produces a 2D image of the shaft excavation by calculating the distance between each sensor and the excavation by measuring the wave speed in slurry at each measurement depth. SHAPE testing was performed on test drilled shaft #1 (see Figure 12[a]), and the calculated 2D profile from the results are displayed during testing (see Figure 12[b]). SHAPE specifications and data are shown in Appendix C.



shaft sidewall consisting of a weak sandy soil after performing the SHAPE and SQUID testing. SHAPE results in Appendix C (see Figure 69) found that the diameter at the top and at the bottom of the shaft is 4 ft and 3 ft, respectively, which is less than the 4 ft diameter of the auger used to drill the shaft. Therefore, the concrete volumes calculated using the results from SHAPE do not appear reasonable for this particular shaft.

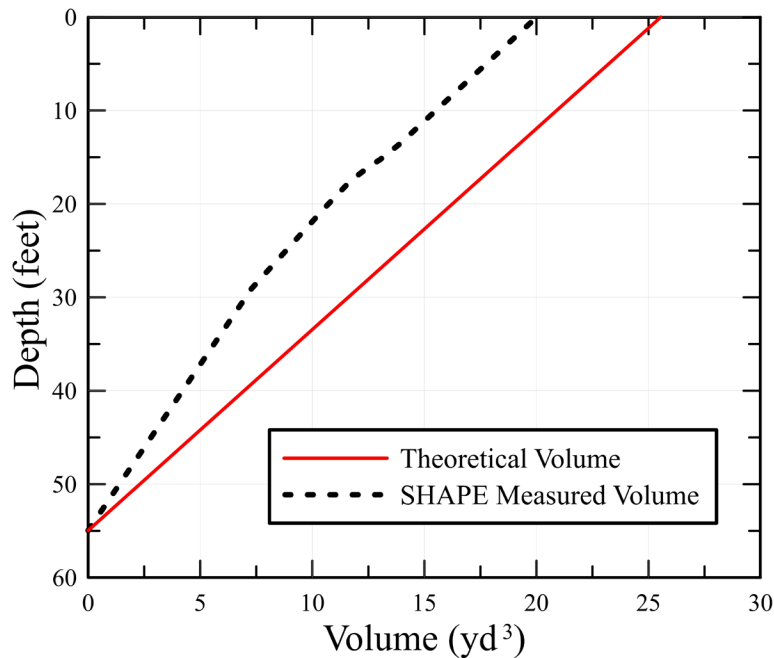


Figure 13. Graph. SHAPE data used to estimate shaft volume with depth for comparison with the theoretical value of test shaft #1.

SQUID Testing

SQUID, or the shaft quantitative inspection device, quantitatively measures the soft material or clay and gravel thickness that may be covering the bearing strata at the bottom surface. The output of SQUID is force and displacement. The entire test can be completed very quickly, typically less than 30 minutes. SQUID consists of three displacement sensors and three cone penetrometers. The SQUID test consists of mounting the device on a Kelly bar or winch system and lowering it into a drilled hole. Once the SQUID is located at the bottom of the hole, the buoyant weight of the Kelly bar will transfer sufficient force for the probes to penetrate the clay and gravel and bearing layers and for the displacement plates to retract. The signals from the three displacement sensors and three cone penetrometers are digitally processed and wirelessly sent to the SQUID tablet. The inspector, engineer, or contractor can then make an immediate decision as to the borehole acceptance, additional clean-out requirement, or additional drilling. Accurate, real-time force versus displacement measurements are plotted and displayed digitally in the SQUID tablet. Figure 14 shows SQUID testing performed on test drilled shaft #1.



(a)



(b)



(c)

Figure 14. Photo. SQUID test performed at test drilled shaft #1 (a) showing the SQUID device before installing it inside the drilled shaft, (b) while installing the device inside the drilled shaft, and (c) after removing the device from the drilled shaft.

Testing was performed two times at one location in the bottom of the drilled shaft at the center. SQUID results indicate that the clay and gravel thickness at the bottom of the shaft ranges between 3.27 to 4.71 in. and between 0.25 to 0.76 in. for run 1 and 2, respectively. After the SQUID testing was performed, a sound indicating a collapse of the drilled shaft sidewall consisting of a weak sandy soil was observed. Therefore, the depth to the bottom of the shaft was measured again using a weighted tape and the soft toe was found to be about 6 ft instead of the design thickness of only 6 in. Because of this, SQUID testing does not provide information on what happened after the test was performed. SQUID specifications and data are shown in Appendix C.

CORING OF TEST SHAFT #1

Coring of test drilled shaft #1 was performed on November 9, 2020. The core diameter was 2 in. The core location was chosen near the center of the drilled shaft. Figure 15 shows the as-built coring of test drilled shaft #1. Figure 16 shows a photograph of the concrete cores obtained from test drilled shaft #1. Inspection of the cores show the start and end of a defect between depths of 32 ft 1 in. and 32 ft 7 in. This defect was observed in the field as broken-up concrete with some gravel and has a length of 6 in. No other defect was observed of the cores obtained from the middle of the drilled shaft. However, the coring revealed that the drilled shaft ended at a depth of 45 ft 7 in., where the core barrel sank under its own weight, indicating the end of concrete and start of the soil that formed the soft toe.

**AS-BUILT
TEST SHAFT 1 (TS-1) (CORING)
I-72, DECATUR IL
FINE GRAINED OVERBURDEN**

SHAFT LENGTH = 50'
SHAFT DIAMETER = 48"
REBAR CAGE LENGTH = 53'
REBAR CAGE DIAMETER = 42"

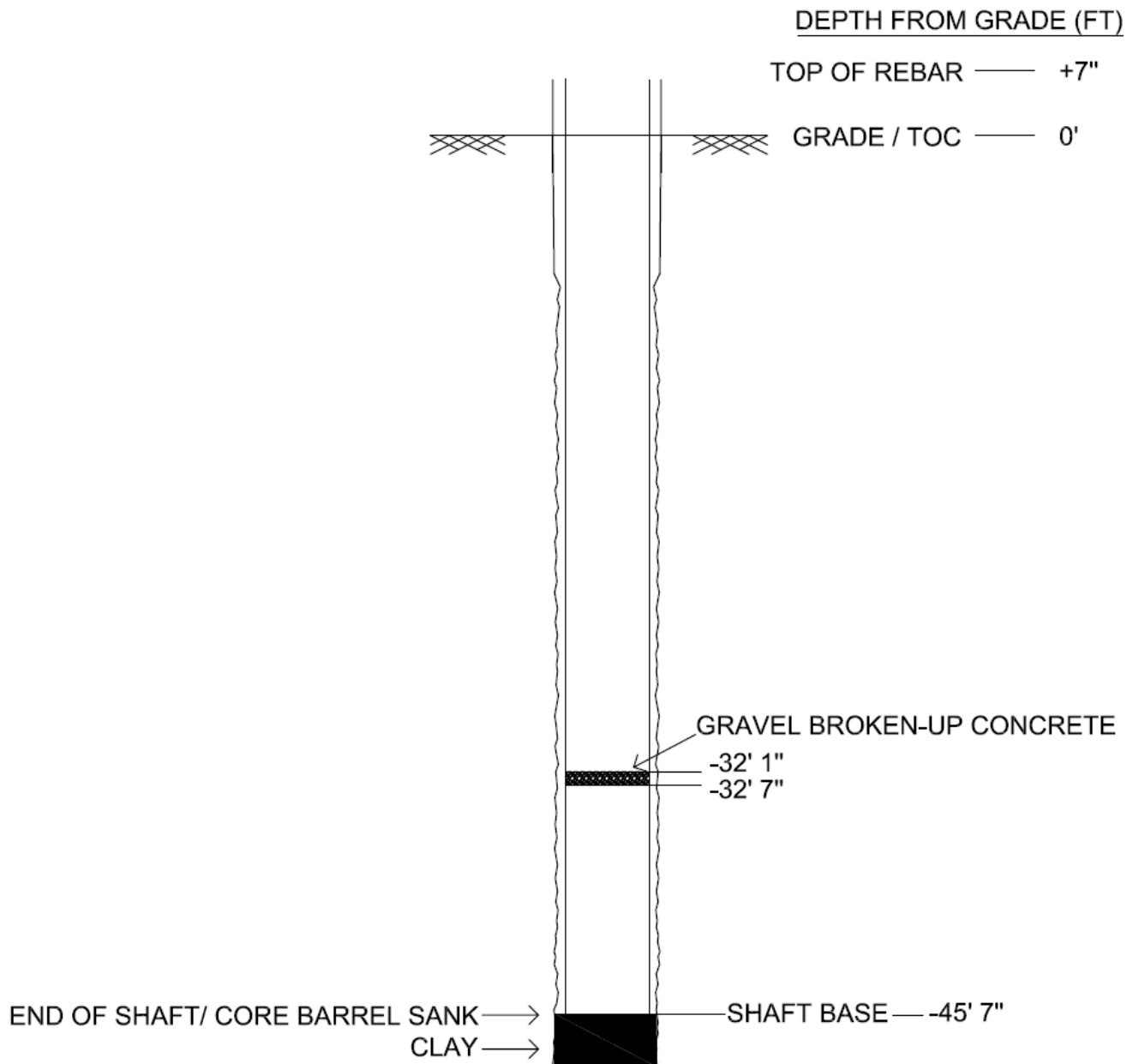


Figure 15. Illustration. As-built concrete coring of test shaft #1.



Figure 16. Photo. Cores obtained from coring test drilled shaft #1 showing the start and end of the observed defect between 32 ft 1 in. and 32 ft 7 in. depth.

SUMMARY

This chapter discusses the construction and testing of test drilled shaft #1 located along I-72 in Macon County, Illinois. In summary, Consultant A's TIP interpretation and Consultant B's CSL interpretation provide similar identification and observation of the installed defects. However, UIUC's interpretation of the TIP test results provided the best detection of all defects, except for the 1.5 ft tremie pipe raise at a depth of 8 ft. The following paragraphs explain this conclusion.

The following defects were installed in the test shaft and then TIP, CSL, SHAPE, SQUID, and concrete coring testing were performed to evaluate which integrity test better detected the following pre-planned defects: (1) shifted rebar cage from ground surface to a depth of 24 ft, (2) tremie pipe raise at 8 ft, (3) tremie pipe raise at 29 ft, and (4) soil added at the bottom of the shaft to create a soft toe. Test drilled shaft #1 has a length of 50 ft and a 4 ft diameter and was equipped with four CSL access tubes and four TIP thermal wires. The test results were collected by Consultant A and Consultant B for TIP and CSL testing, respectively, and were reanalyzed herein. Table 7 shows a summary of the findings from Consultant A and the UIUC research team for TIP testing and from Consultant B and UIUC for CSL testing. As expected, Table 7 shows that UIUC's interpretation of the TIP test results provided the best detection of all defects, except for the 1.5 ft tremie pipe raise at a depth of 8 ft. For test drilled shaft #1, analysis of the temperature profiles with depths at one-half the time to peak temperature provided better detection of the defects than at the peak temperature. Concrete coring found only two defects, and therefore, integrity testing can provide a better insight of the drilled shaft quality than coring. If coring is used, the core should be located near the rebar cage and not near the center of the shaft. SHAPE and SQUID tests do not provide information on what happened to the drilled shaft after testing, as the case for drilled shaft #1 where a sidewall collapse occurred right after the SHAPE and SQUID tests. In other situations, SHAPE and SQUID tests may be more useful.

Table 7. Summary TIP Testing and CSL Score Card for Test Drilled Shaft #1

Defect	Data Interpretations			
	Consultant A's TIP	UIUC's TIP	Consultant B's CSL	UIUC's CSL
Shaft diameter change at 7 ft	Detected oversized diameter to bottom of casing at ~7 ft	Detected well	Detected poor concrete to depth of 3 ft	Detected poor concrete from 3 to 6 ft
4 in. offset cage at 2 to 12 ft	Not detected due to oversized diameter	Detected via wire #4 and dissipates at wire #1	Not detected	Not detected
1.5 ft tremie raise at ~8 ft	Not detected	Inconclusive	Not detected	Not detected
2.5 in. offset cage ~15 to 25 ft	Inconclusive	Detected via all wires	Not detected	Not detected
2.25 hours cold joint at ~29.0 ft at the beginning of delay and 28.3 ft after concrete resumed	Possibly reduced diameter ~28 ft	Detected well	Detected	Detected around 30 ft
3.2 ft tremie raise at ~33 ft	Possibly reduced diameter ~32 ft	Detected well	Detected	Detected around 35 ft
44 to 50 ft soft toe (6.4 ft deep)	Below 45 ft is zero heat—detected well	Detected well	Detected well	Detected

CHAPTER 5: TEST DRILLED SHAFT #2

INTRODUCTION

The location of test drilled shaft #2 is shown in Figure 82 of Appendix D. A detailed longitudinal profile of the initial design of test drilled shaft #2 is shown in Figure 17. Test shaft #2 is located 0.5 miles north of Sherrill Road along IL-47 in Kendall County, Illinois. In particular, Figure 17 shows the design of the drilled shaft with detail of the temporary casings used, shaft diameter and length, and a rock socket. Figure 17 also shows the planned defects included in this test shaft—soil inclusions of different thicknesses and geometric shapes—which were added at three different locations to the test shaft. The main design parameters for test drilled shaft #2 are a length of 24 ft, shaft diameter of 6 ft, rebar cage length and diameter of 27 ft and 5 ft, respectively, and a 6.5 ft diameter temporary casing to a depth of 3 ft.

The drilled shaft was designed to have a good base clean out. Concrete was poured for test drilled shaft #2 using the dry method with no tremie raises. The following defects were added to the construction process. At a depth of 3 ft (bottom of casing), 6 in. thick soil cuttings were added between the temporary casing and the rebar cage annulus over one-quarter of the drilled shaft circumference. At a depth of 11 ft, an 8 in. thick soil inclusion was added and uniformly distributed across the drilled shaft diameter. At a depth of 18 ft, another soil inclusion was added with a planned thickness of 2 in. and uniformly distributed across the drilled shaft diameter. These soil inclusions consisted of soil and gravel and were added by pausing the concrete placement, shoveling the soil and gravel into the drilled shaft, and then resuming concrete placement.

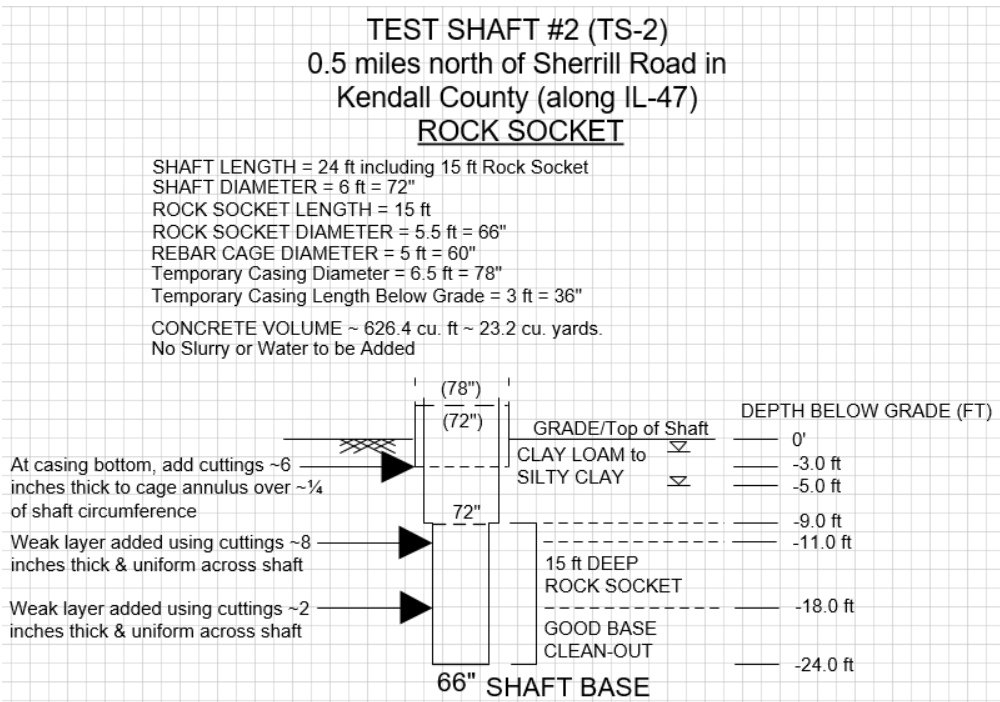


Figure 17. Illustration. Initial design of test drilled shaft #2 located 0.5 miles north of Sherrill Road in Kendall County, Illinois (along IL-47).

Figure 18 shows the design cross section of test drilled shaft #2, with the details of the rebar cage included. The outside diameter of the rebar cage is 5 ft with a 7 in. clear distance between the 22 longitudinal rebars, which are #8 vertical rebars and #6 hoops at 12 in. vertical spacing. Figure 18 also shows the six CSL steel access tubes installed inside the rebar cage, i.e., one per foot of shaft diameter, and each with an outside diameter of 2 in. for CSL.

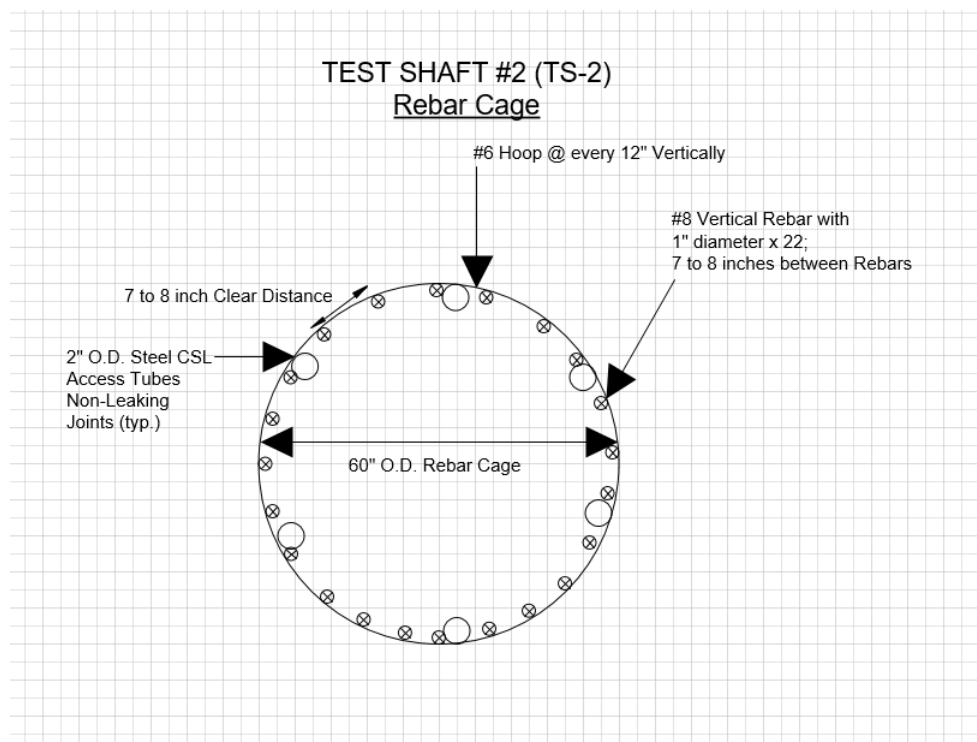


Figure 18. Illustration. Initial design cross section of test drilled shaft #2 with reinforcement detail.

TEST SHAFT #2 CONSTRUCTION

Test drilled shaft #2 was poured on October 29, 2020, using the dry method, and the concrete was placed via a pump truck and tremie pipe. The placed concrete volume is 26.9 yd³. Drilled shaft information, soil boring logs, and installation details are shown in Appendix D. The rebar cage was instrumented with 12 thermal wire cables (two per foot of shaft diameter instead of the typical one per foot of shaft diameter) extending to the bottom of the cage. The wires were numbered clockwise, with wire 1 corresponding to the wire in the northeast position. (See TIP testing logs for the location of each wire in Appendix D.) Appendix D also shows a sketch of the TIP wires' configuration with wire-wire distances, the serial number for each wire, and general drilled shaft information. The rebar cage was fitted with six CSL tubes (one per foot of shaft diameter) extending to the bottom of the cage. Appendix D presents a diagram of the access tube configuration for CSL, including the CSL tube numbers and various CSL testing combinations.

The temporary casing measured 75.5 in. in diameter and extended to a depth of 3.5 ft along with another 69 in. diameter temporary casing that extended to a depth of 8.5 ft. The final 16.5 ft of the drilled shaft consisted of an uncased 66 in. diameter rock socket.

Figure 19(a) shows installation of the 6.5 ft outer diameter temporary casing, and Figure 19(b) shows the start of excavation after placement of the temporary casing. Figure 20(a) shows the 5 ft diameter rebar cage with 6 CSL access tubes and 12 TIP thermal wires already installed before placement in the drilled shaft. Figure 20(b) shows the 5 ft diameter rebar cage with six CSL tubes and 12 TIP thermal wires after concrete pouring.



(a)



(b)

Figure 19. Photo. Photographs showing (a) installation of 6.5 ft outer diameter temporary casing and (b) start of excavation after placing the temporary casing in the shaft.



(a)



(b)

Figure 20. Photo. Photographs showing (a) 5 ft diameter rebar cage with 6 CSL tubes and 12 TIP thermal wires installed before placement in the shaft and (b) installed rebar cage after concrete pouring and connection of TIP readout boxes.

Figure 21 shows the as-built details of test drilled shaft #2 after construction. The actual length of casing below the ground surface is 3.5 ft and a tremie raise of 1.5 ft occurred at 5.5 ft. Figure 21 also shows the 6 in. thick soil and rock cuttings added to the rebar cage annulus over the southeast quarter of the drilled shaft circumference between the rebar cage and temporary casing at a depth of 3.5 ft. Finally, Figure 21 includes the 8 in. and 4 in. thick soil inclusions added by hand at depths of 14 ft and 20 ft, respectively. After installation of the soil inclusions, concrete pouring was resumed about 6 in. above each soil inclusion. The drilled shaft base had a good base clean out before installation of the rebar cage.

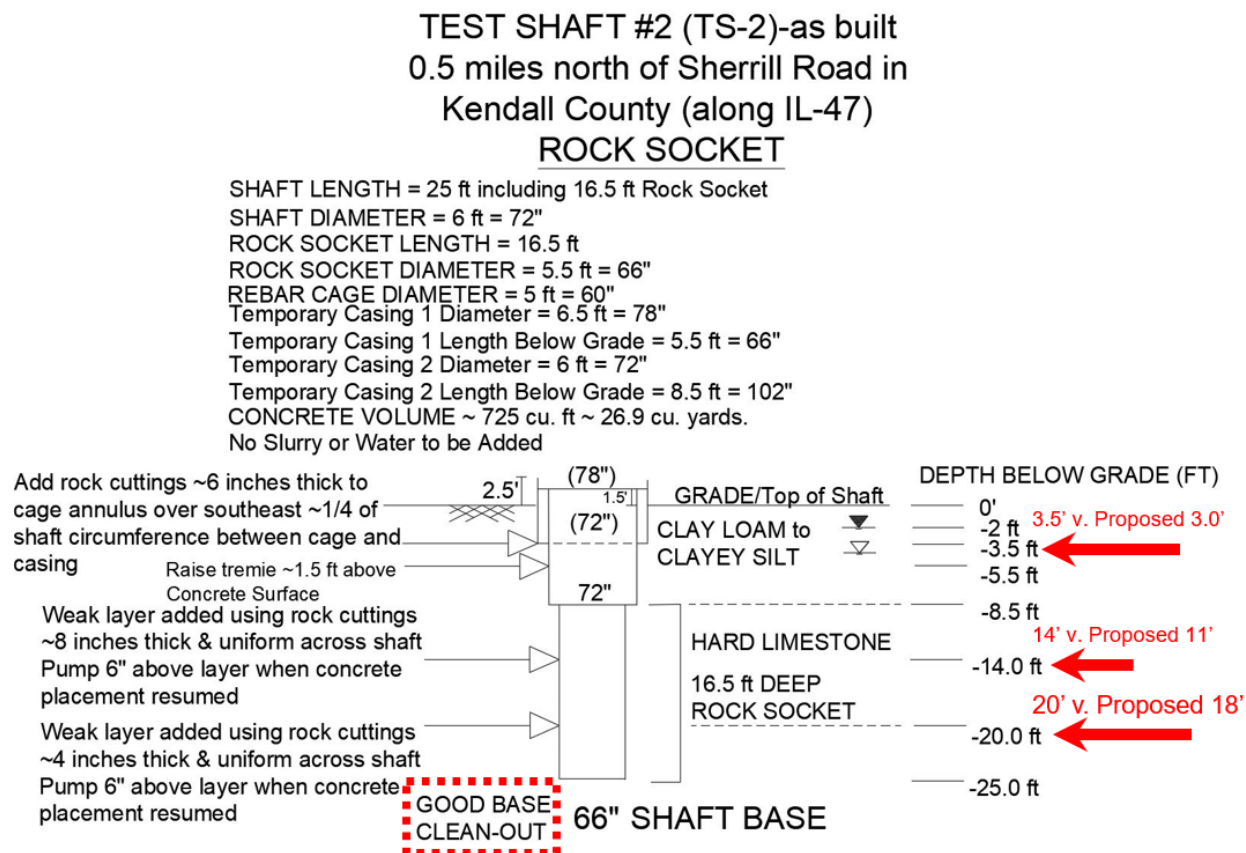


Figure 21. Illustration. As-built diagram for test drilled shaft #2.

TIP TESTING

The TIP data summarized in this chapter was recorded by Consultant A from October 26 through November 2, 2020. For test drilled shaft #2, 12 thermal wire cables were attached approximately symmetrical around the rebar cage. The thermal wires extend the full length of the drilled shaft rebar cage. Test drilled shaft #2 has twice the number of TIP wires typically used by IDOT (two instead of one thermal wire per foot of drilled shaft diameter) to increase the resolution of the temperature measurements. To identify localized defects within the test shaft, the following analyses of the TIP data were conducted: (1) only considering odd-numbered wires, (2) only considering even-numbered wires, and (3) considering all wires together. The odd-, even-, and all-wire analyses have been independently analyzed by different individuals at Consultant A as well as the research team.

Temperature at Rebar Cage for Ideal Drilled Shaft

Similar to test drilled shaft #1, the temperature at the rebar cage that corresponded to an ideal drilled shaft with the same diameter as test drilled shaft #2 was investigated, and the results are summarized in Appendix D. Similar to test drilled shaft #1, the predicted ideal temperatures are conflicting, so Consultant A's evaluation method for the TIP testing data was adopted to evaluate the integrity of test drilled shaft #2. Developing the temperature profile for an ideal drilled shaft to facilitate assessing shaft integrity is a topic of future research.

Consultant A's TIP Results

Consultant A's results for test drilled shaft #2 include thermal results, which are presented in Appendix D. Test drilled shaft #2 achieved peak temperature approximately 37.5 hours after completion of concrete placement. The optimal time for drilled shaft analysis usually occurs between one-half the time to peak temperature and peak temperatures. When anomalies are indicated in the thermal data, the analyses are normally performed closer to one-half the time to peak temperature, which is the time of greater differences in temperature and contrasts between the temperatures are easier to identify.

Odd-Numbered Wire Analysis

Consultant A's radius analysis was performed near one-half the time to peak temperature or approximately 18 hours after concrete placement (see Figure 22(a)). Wire 6, serial number 57994 PF, appears to have been damaged during the installation process, because no data is available below a depth of 11 ft. In Figure 22(a) the thermal wires are labelled 1 through 6, but these are the six odd-numbered wires, i.e., 1, 3, 5, 7, 9, and 11, installed in the rebar cage.

Consultant A's odd-wire interpretation indicates the effective average radius is generally as expected from the top of the drilled shaft to a depth of approximately 13 ft. Below a depth of 13 ft, multiple temperature reductions are observed (see Figure 22(a)). The most significant reduction is observed near a depth of 14 ft, where the thermal model indicates a reduction down to the reinforcing cage, as shown in Appendix D. Data from all the odd thermal wires show evidence of the reduction. A second reduction is observed near a depth of 20 ft, which is also observed by all the odd wires. This reduction appears most significant near wires 1 and 5, where the TIP model indicates minimal concrete cover on the rebar cage. A reduction below the nominal radius is also predicted near the base of the drilled shaft near a depth of 24 to 25 ft. This reduction appears to be localized near the location of wires 4 and 5.

Early in the curing process up to the time of approximately one-half the time to peak temperature, Consultant A observed temperature reductions near wire 2 at a depth of 3 ft and by all odd wires near a depth of 6 ft. The reduction at a depth of 6 ft is most significant near wires 5 and 6. As observed on prior test drilled shafts where manufactured defects were installed (Boeckmann & Loehr, 2018), these reductions were interpreted by Consultant A as sandbags that equate to a low cross-sectional area that heat up during the curing process and become less evident with time.

Even-Numbered Wires

Consultant A's radius analysis was also performed near the one-half the time to peak temperature approximately 18.75 hours after concrete placement for the even thermal wires (see Figure 22[b]). In Figure 22(b), the thermal wires are labelled 1 through 6, but these are six even-numbered wires, i.e., 2, 4, 6, 8, 10, and 12, installed in the rebar cage.

Consultant A's TIP-derived model indicates the average effective radius is generally as expected relative to the planned geometry to a depth of 12 ft, as shown in Appendix D. Effective radius reductions were identified from 13 to 15 ft below the top of the drilled shaft and from 20 to 21 ft below the top of the drilled shaft. The reduction at 13 ft occurs in all even and odd wires and likely affects most or all of the cross section. The reduction at 20 ft occurs more strongly in even wires 4, 5, and 6, the west side of the drilled shaft. A smaller reduction in effective radius is also calculated at the base of the drilled shaft.

Additionally, Consultant A observed minor diameter reductions at 6 ft below the top of the concrete in all even and odd wires, and a small temperature reduction in the early data at 2 ft below the top of concrete in wires 2 and 3. Shifting of the rebar cage is also evident from 10 ft below the top of the drilled shaft to the bottom of the cage, with even-numbered wires 3 and 4 in Figure 22(b) closer to the center of the drilled shaft, i.e., higher temperatures, and even-numbered wires 1 and 6 closer to the soil, i.e., lower temperatures.

All Twelve Thermal Wires

Consultant A's radius analysis was performed slightly beyond one-half the time to peak temperature or approximately 20.5 hours after concrete placement for all 12 thermal wires installed (see Figure 22[c]). Thermal wire 11, serial number 57994 PF, appears to have been damaged during the installation process, which is the same as odd-numbered wire 6 shown in Figure 22(a).

Figure 22(c) shows a reduction in temperatures between 12 and 16 ft, which Consultant A's TIP interpretation model represents as a reduction in effective drilled shaft radius 12 to 16 ft below the drilled shaft top, as shown in Appendix D. The temperature reduction is observed in all wires and is most strongly indicated around wires 1, 2, 3, 4, and 12.

A second smaller radius reduction is evident from a depth of 19 to 21 ft. This radius reduction is most strongly indicated in thermal wires 9, 10, and 12. There is also a radius reduction evident in the lower one foot of the drilled shaft, as strongly indicated near thermal wires 7, 8, 9, and 10. Below the upper casing there are indications of a slight cage shift, with thermal wire 12 closer to the soil (lower temperature) and thermal wire 6 near the drilled shaft center (higher temperature).

Consultant A found that small reductions in temperature are evident at 3 and 7 ft below the drilled shaft top shortly after placement. The reduction at 3 ft was observed near wires 3 and 4, and the reduction at 7 ft is evident near wires 9, 10, 11, and 12. The magnitude of the reductions at one-half the time to peak temperature would likely not be addressed under typical analysis procedures.

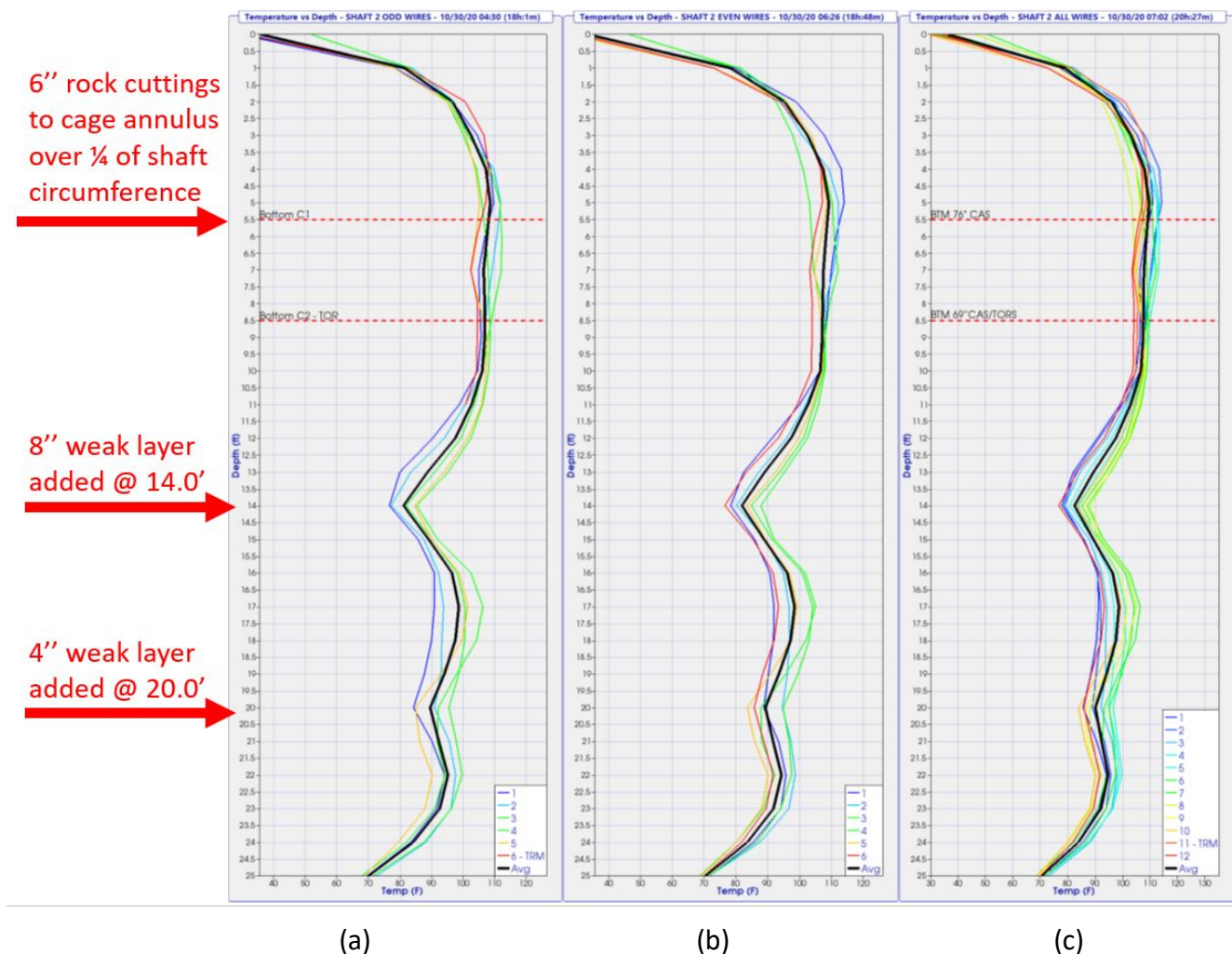


Figure 22. Graph. Temperature versus depth profile in test drilled shaft #2 with red arrows indicating the location of the defects for (a) six odd wires at 18 hours and 1 minute, (b) six even wires at 18 hours and 48 minutes, and (c) all 12 thermal wires installed in test shaft #2 at 20 hours and 27 minutes after concrete placement.

UIUC's Interpretation of TIP Results

Table 8 shows a summary of the defects identified by Consultant A and the research team using all TIP wires for test drilled shaft #2. A detailed discussion and analysis of data from the odd wires, even wires, and all wires performed by the research team is summarized in Appendix D. Table 8 shows good agreement between Consultant A and the research team for all defects. Nevertheless, it is important to note that using double the required number of thermal wires in TIP testing did not provide any additional insights to the integrity of the shaft. Therefore, there is no need to use more thermal wires than the required number of thermal wires (see Appendix F for IDOT Standards).

Table 8. Summary of TIP Data Interpretation by Consultant A and UIUC for Test Drilled Shaft #2

Defect	Consultant A Interpretation (Odd-Numbered Wires)	Consultant A Interpretation (Even-Numbered Wires)	Consultant A Interpretation (All Wires)	UIUC Interpretation (All Wires)
6 in. rock cuttings in cage annulus over 1/4 of circumference added at 3.5 ft	Inconclusive	Inconclusive	Detected	Detected
Tremie pipe raise at ~5.5 ft w/max free-fall ~1.5 ft	Detected	Inconclusive	Detected	Inconclusive
Diameter change from 72 in. to 66 in. at 8.5 ft—rock socket	Not Detected	Not Detected	Not Detected	Not Detected
8 in. soil inclusion added at 14 ft concrete pumped 6 in. above soil inclusion	Detected	Detected	Detected	Detected
4 in. soil inclusion added at 20 ft concrete pumped 6 in. above soil inclusion	Detected	Detected	Detected	Detected

CSL TESTING

As with test drilled shaft #1, Consultant B performed CSL testing in test drilled shaft #2. The CSL was performed in accordance with ASTM D6760 (2016) using the cross-hole ultrasonic module (CHUM) manufactured by Piletest. Test drilled shaft #2 concrete was placed on October 29, 2020, and CSL testing was performed 15 days after that on November 13, 2020. Test drilled shaft #2 contains six access tubes for CSL testing. The access tubes consist of 2 in. diameter steel pipes in 10 ft length segments threaded together, and they extend to the bottom of the rebar cage. Appendix D presents the access tube arrangement for test drilled shaft #2.

The initial CSL testing was performed on 15 combinations of access tubes. CSL measurements were taken along the length of the access tubes at 1 in. depth increments. The average height of steel access tube stickup above the top of concrete is approximately 5.7 ft at the time of CSL testing. The average steel access tube bottom elevation for the drilled shaft is 563.9 ft or a depth below ground surface of 25 ft. Based on the available data, the drilled shaft bottom elevation is at approximately 588.6 ft. The distance between the average bottom elevation of the access tubes and the estimated bottom elevation for the drilled shaft is approximately 0.3 ft.

A review of the drilled shaft installation logs in Appendix D for test drilled shaft #2 reveals the following information for CSL interpretation:

- No significant deficiencies or irregularities were observed during concrete placement.
- An apparent concrete volume difference of 3.4 yd³ was observed between apparent volume of concrete placed (27 yd³) and the theoretical concrete volume (23.6 yd³). This is an apparent concrete over-pour of approximately 14%. The theoretical concrete volume was determined from various drilled shaft diameters and lengths provided and is based on a bottom of shaft elevation at 563.6 ft and a top of shaft elevation of 588.6 ft, i.e., a shaft length of 25 ft. One explanation for the concrete volume difference is the apparent volume of concrete placed includes excess concrete that is pumped until it overflows over the top of the casing as well as trying to subtract the concrete left in the truck. It is sometimes difficult to quantify these amounts and should be considered an estimate because the results may affect the amount of concrete over-pour calculated.

Consultant B's CSL Results

In general, Consultant B's interpretation of the CSL test results for test drilled shaft #2 show only minor deviations in FAT and relative energy in the tested tube combinations along the length of the drilled shaft. These minor fluctuations are less than 10% and, therefore, are insignificant according to FHWA-NHI 18-024 (Brown et al., 2018), which is discussed below. There are three exceptions within test drilled shaft #2, where zones of increased FAT and decreased relative energy were identified by Consultant B within a majority of the tested access tube combinations. A summary of the exceptions identified by Consultant B are presented in Table 9 along with their CCRC rating. In addition to the CCRC rating, the table presents the rating based on FHWA-NHI 18-024 (Brown et al., 2018). As described for test drilled shaft #1, the new evaluation considers three different classes—A, B, and C—which also rely on reductions in relative energy and increases in FAT. The 2018 criteria are also shown on the individual CSL results in Appendix D.

Table 9. Consultant B's CSL Assessment of Test Drilled Shaft #2

Depth Below Top of Shaft (ft)	Tube Combinations	CCRC Rating	2018 FHWA	Assessment
12 to 14	All except 1–5	Poor/Defect	Class B / Class C	Likely defect/needs additional evaluation
18.5 to 19.5	All	Poor/Defect	Class B / Class C	Likely defect/needs additional evaluation
24 to BOS	All except 1–3, 2–3, 2–5, 2–6	Questionable	Class B	Potential defect/needs additional evaluation

Figure 23 presents Consultant B's CSL interpretation results for test shaft #2 with the defect locations indicated with red arrows to facilitate interpretation of the test results (profiles 1–2 on the left, 1–3 in the center, and 1–4 on the right side). The figures for the other access tube combinations used for the CSL are shown in Appendix D.

Average concrete apparent wave speeds were calculated with an average value around 12,000 ft/sec, which is in the range of good concrete according to several published guidelines for relating concrete quality with compression wave velocities (Brown et al., 2018). As mentioned in Chapter 4, this comparison should only be used as a guide for evaluating concrete compressive strength.

Based on Consultant B's CSL testing and analysis and their review of available drilled shaft installation records, Consultant B identified three anomalies in test drilled shaft #2, as outlined in Table 9 and summarized below, based on the following observations:

- There are increased values of FAT and decreased relative energy in several areas of test shaft #2 with CCRC ratings ranging from Questionable to Poor/Defect (P/D).
- Several areas of concrete are classified as Class B and Class C within test drilled shaft #2.
- No significant anomalies were observed in the remainder of the CSL test results.
- Overall, test drilled shaft #2 has an average concrete quality rating of "Good," as determined using the average apparent wave speed calculations for near the top of the drilled shaft.

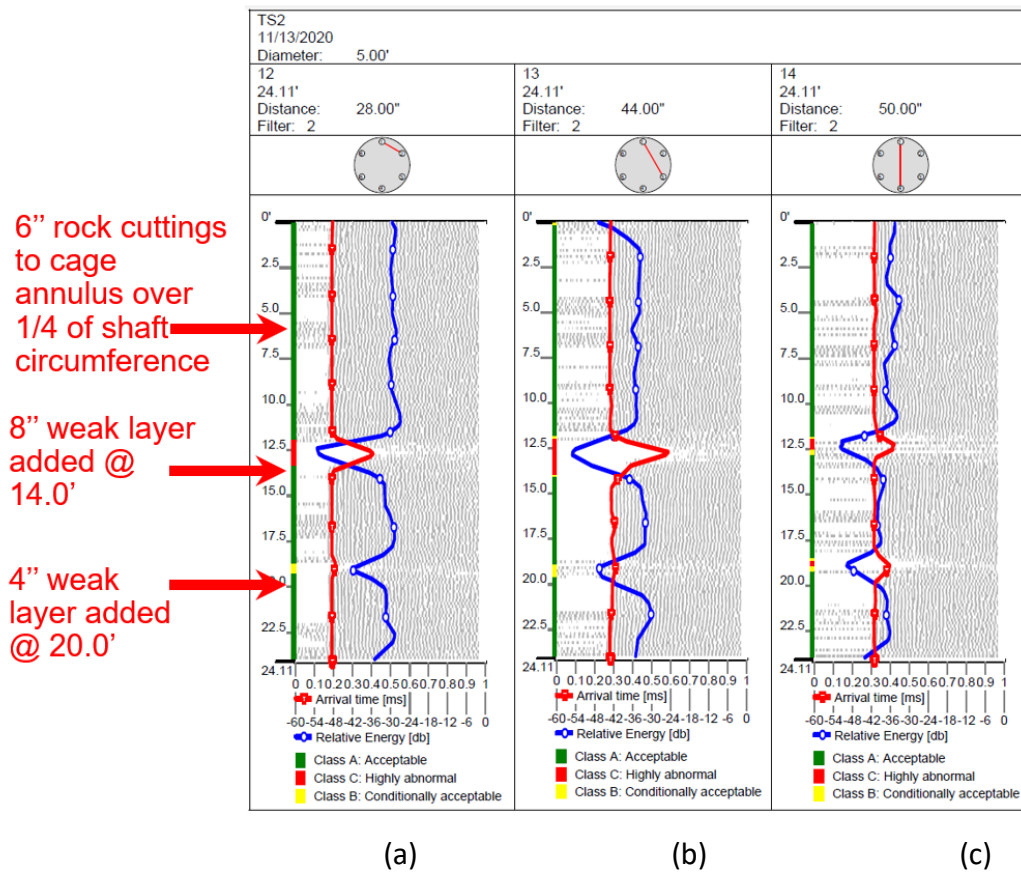


Figure 23. Graph. Consultant B's CSL results for test shaft #2 for (a) along an edge of the shaft (profile 1-2), (b) across the shaft (profile 1-3), and (c) across the middle of the shaft (profile 1-3), with red arrows showing installed defect locations.

UIUC's Interpretation of Consultant B's CSL Results

Table 10 shows a summary of the defects and the CSL interpretation by Consultant B and the UIUC research team. The only defects that were well detected by CSL are those that were created at 14 ft and 20 ft. A detailed discussion and analysis of the Consultant B CSL data performed by the research team is summarized in Appendix D. Table 10 shows excellent agreement between the Consultant B and UIUC interpretations of the CSL data.

Table 10. Summary of CSL Interpretation by Consultant B and UIUC for Test Drilled Shaft #2

Defect	Consultant B Interpretation	UIUC Interpretation
6 in. rock cuttings in cage annulus over 1/4 of circumference added at 3.5 ft	Not Detected	Not Detected
Tremie pipe raise at ~5.5 ft w/ max free-fall ~1.5 ft	Not Detected	Not Detected
Diameter change from 72 in. to 66 in. at 8.5 ft—rock socket	Not Detected	Not Detected
8 in. soil inclusion added at 14 ft concrete pumped 6 in. above soil inclusion	Detected	Detected
4 in. soil inclusion added at 20 ft concrete pumped 6 in. above soil inclusion	Detected	Detected

Consultant A's CSL Results

Consultant A also conducted CSL on test drilled shaft #2 and was provided with the drilled shaft construction records, which are included in Appendix D. Test drilled shaft #2 has a length of 25 ft and a measured average tube length of 24.8 ft with a 0.2 ft distance between tube bottom and drilled shaft bottom. Test drilled shaft #2 was tested by Consultant A on November 5, 2020, six days after its installation. The apparent distance between the CSL access tube bottom and drilled shaft bottom is based on the drilled shaft lengths calculated from the top and bottom of drilled shaft elevations in the installation records and the embedded tube lengths calculated from Consultant A's averaged field measurements. A blockage was encountered by Consultant A in access tube #3 of test drilled shaft #2 and its total length was approximately one foot shorter than the rest of the test drilled shaft #2 CSL access tubes.

For test drilled shaft #2, the steel access tubes were labeled 1 through 6 in a clockwise manner, with tube 1 corresponding to the first tube clockwise from due north for each drilled shaft, as shown in Appendix D. The CSL results are referred to as "profiles," with profile 1–2 being the CSL results between the first and second access tubes clockwise from due north. Tests on six perimeter profiles and nine diagonal profiles were performed by Consultant A for test drilled shaft #2. The sonic logging probes were first placed in the water-filled access tubes and lowered to the bottom. They were then raised together as ultrasonic signals were transmitted and received for every 2 in. of probe travel. The location or depth of the probes was electronically recorded by two independent meter wheels

through which the probe cables passed. All depths on the output plots are referenced to the top of the drilled shaft at the time of testing.

Figure 24 shows Consultant A's CSL results for test drilled shaft #2 with defect locations (profile 1–2 on the left and 1–6 on the right side). Each figure for a given combination of access tubes contains two figures. The figure on the left contains the first arrival time (FAT) and relative energy profiles and the right side is the "waterfall diagram." The waterfall diagram shows the positive amplitudes of the record in black and the negative amplitudes in green of the raw data as a function of time. The waterfall diagram is a clearer representation of concrete quality over depth because the blank locations indicate much weaker material.

The figures for the other access tube combinations are shown in Appendix D. Similar to Consultant B's CSL results above, Consultant A's results in Figure 24 show the relative energy with FAT for different combinations between different tube combinations. A sketch of the tube configuration is shown at the top of FAT and relative energy profiles of the left in Figure 24 and also at the top of the waterfall diagram on the right with the green background.

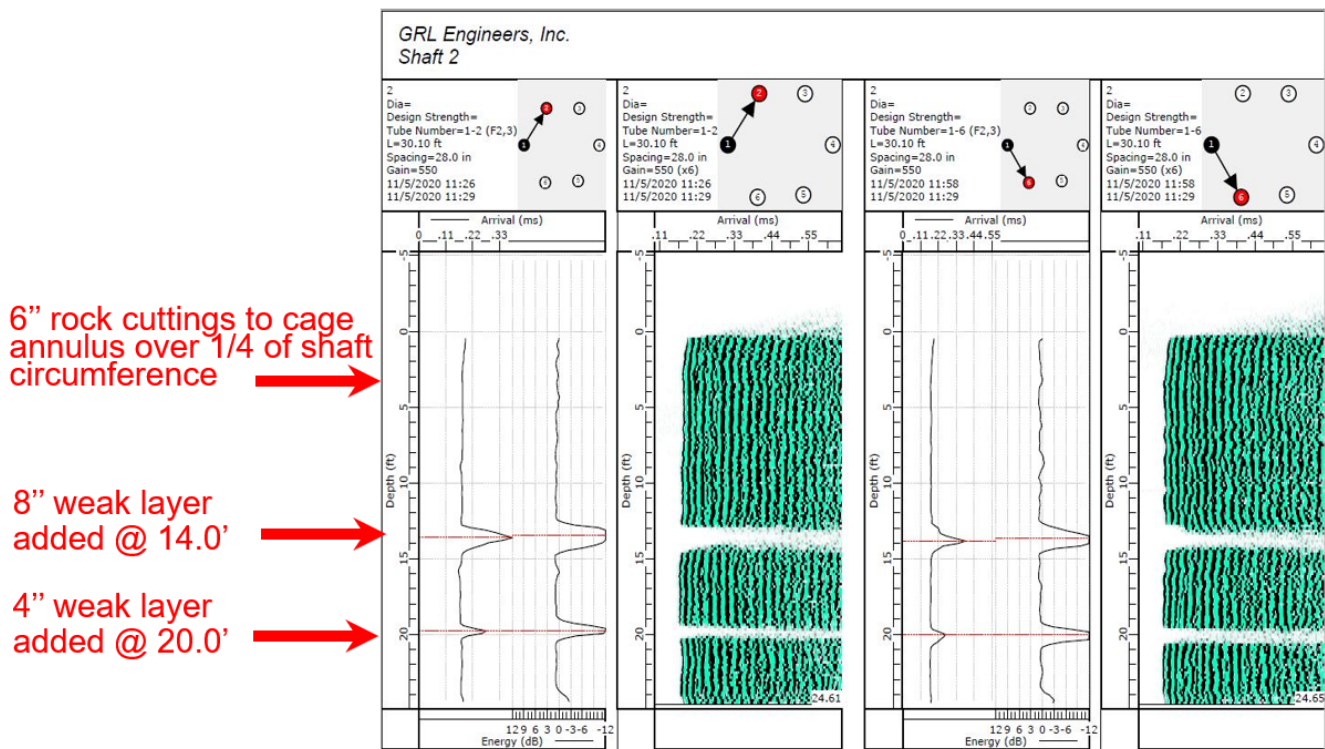


Figure 24. Graph. Consultant A's CSL results for test drilled shaft #2 with defect locations for profile 1–2 on the left and profile 1–6 on the right.

At depths of 12.5 to 15.0 ft below the top of concrete in test shaft #2, all profiles are categorized as Class C by Consultant A, with FAT increases of 100% and energy decreases greater than 12 dB. At depths between 19.0 and 21.0 ft below the top of shaft, 14 of the 15 profiles are categorized as either Class B or Class C quality. Profile 3–4 is the only Class A profile at this depth. Class B quality corresponds to access tube profiles 2–4, 3–5, and 3–6, with FAT increases between 15% and 27% and energy decreases from 9 to 12 dB. The remaining 11 profiles are identified as Class C quality, with FAT increases between 19% and 100% and energy decreases of 9 dB to greater than 12 dB. One access tube profile (5–4), at a depth of 24 ft to the bottom of the CSL tubes, is categorized as Class C, with FAT increases of 20% and energy decreases greater than 12 dB.

UIUC’s Interpretation of Consultant A’s CSL Results

Table 11 compares the defects and CSL interpretation by Consultant A and the UIUC research team. Table 11 shows there is excellent agreement between the Consultant A and UIUC interpretations. In addition, Table 11 shows the only defects that were clearly detected by CSL results are the soil inclusions added at depths of 14 and 20 ft. A detailed discussion and analysis of Consultant A’s CSL data performed by the UIUC research team is summarized in Appendix D.

Table 11. Summary of CSL Interpretation by Consultant A and UIUC for Test Drilled Shaft #2

Actual Drilled Shaft Defect	Consultant A Reported CSL Results	UIUC Interpreted CSL Results
6 in. rock cuttings in cage annulus over 1/4 of circumference added at 3.5 ft	Not Detected	Not Detected
Tremie pipe raise at ~5.5 ft w/ max free-fall ~1.5 ft	Not Detected	Not Detected
Diameter change from 72 in. to 66 in. at 8.5 ft—rock socket	Not Detected	Not Detected
8 in. soil inclusion added at 14.0 ft concrete pumped 6 in. above soil inclusion	Detected	Detected
4 in. soil inclusion added at 20.0 ft concrete pumped 6 in. above soil inclusion	Detected	Detected

CORING OF TEST SHAFT #2

Coring of test drilled shaft #2 was performed on April 19, 2021. The core diameter is 2 in. The core location was chosen near the center of the drilled shaft. Figure 25 shows a diagram of the as-built coring of test drilled shaft #2. The photographs of the defects found while conducting the concrete coring for test drilled shaft #2 are shown in Appendix D. Inspection of the cores show the start and end of a defect between depths of 13.5 and 14.0 ft. This defect was observed in the field as broken-up concrete with some gravel and has a length of 6 in. No other defect was observed of the cores obtained from the middle of the drilled shaft.

TEST SHAFT #2 (TS-2)-as built (Coring) 0.5 miles north of Sherrill Road in Kendall County (along IL-47) ROCK SOCKET

SHAFT LENGTH = 25 ft including 16.5 ft Rock Socket
 SHAFT DIAMETER = 6 ft = 72"
 ROCK SOCKET LENGTH = 16.5 ft
 ROCK SOCKET DIAMETER = 5.5 ft = 66"
 REBAR CAGE DIAMETER = 5 ft = 60"
 Temporary Casing 1 Diameter = 6.5 ft = 78"
 Temporary Casing 1 Length Below Grade = 5.5 ft = 66"
 Temporary Casing 2 Diameter = 6 ft = 72"
 Temporary Casing 2 Length Below Grade = 8.5 ft = 102"
 CONCRETE VOLUME ~ 725 cu. ft ~ 26.9 cu. yards.
 No Slurry or Water to be Added

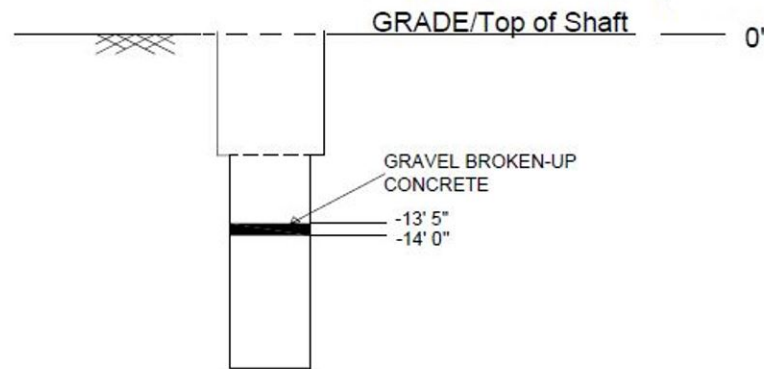


Figure 25. Illustration. As-built concrete coring of test shaft #2.

This finding indicates that the defect at 20 ft was detected by CSL and TIP tests but was not detected by coring. This is probably due to the coring being located near the middle of the drilled shaft even though the defects were created by hand while shoveling clay and gravel into the shaft from the ground surface. The shoveled clay and gravel could have been concentrated along the drilled shaft edges rather than in a uniform way or the tremied concrete displaced the soil from near the center of the shaft to toward the rebar cage. As a result, coring did not detect the added soil near the center of the test drilled shaft, although TIP and CSL testing did. Based on the coring activities conducted during this project, it is recommended that concrete cores be located near the rebar cage and not near the center of a drilled shaft to assess integrity.

SUMMARY

This chapter discusses the construction and testing of test drilled shaft #2 located 0.5 miles north of Sherrill Road in Kendall County, Illinois, along IL-47. In summary, TIP testing was better than CSL testing at detecting the defects outside the rebar cage such as the planned defect at 3.5 ft. Both TIP and CSL testing were able to identify the defects inside the rebar cage, e.g., the 8 in. and 4 in. soil inclusion at 14 ft and 20 ft, respectively. The following paragraphs explain this conclusion.

The following defects were installed in the test shaft and then TIP testing, CSL testing, and concrete coring were performed to evaluate which integrity test better detected these pre-planned defects: (1) soil added to casing annulus at a depth of 3.5 ft, (2) tremie pipe raise at 5.5 ft, (3) soil added at 14 ft, and (4) soil added at 20 ft. The test drilled shaft #2 has a length of 25 ft and a 6 ft diameter and was equipped with 6 CSL access tubes and 12 TIP thermal wires. The test results were collected by Consultant A and Consultant B for TIP and CSL testing, respectively, and were reanalyzed herein.

Table 12 compares the findings/interpretations from Consultant A and the UIUC research team for TIP testing and from Consultant B, Consultant A, and UIUC for CSL. The interpretations of CSL results by Consultant A and Consultant B are similar and in agreement with the UIUC interpretations. For test drilled shaft #2, analysis of the temperature profiles with depth at one-half of the time to peak temperature provided better detection of the defects than the time of peak temperature. It is important to note that using double the required number of thermal wires in TIP testing did not provide almost any additional insights to the integrity of the shaft. Therefore, there is no need to use more thermal wires than the required number of thermal wires. (See Appendix F for IDOT specifications.) For test drilled shaft #2, there was no defect installed at the bottom of the drilled shaft, so the usual temperature roll-off at the shaft bottom is not a drawback of TIP testing. This potential limitation is addressed in the next chapter for test drilled shaft #3, where a defect was created at the bottom of the drilled shaft.

Table 12. Summary TIP Testing and CSL Score Card for Test Drilled Shaft #2

Defect	Data Interpretations					
	Consultant A's TIP	UIUC's TIP	Consultant A's CSL	UIUC's CSL	Consultant B's CSL	UIUC's CSL
6 in. rock cuttings in cage annulus over 1/4 of circumference added at 3.5 ft	Detected	Detected	Not Detected	Not Detected	Not Detected	Not Detected
Tremie pipe raise at ~5.5 ft w/ max free-fall ~1.5 ft	Detected	Inconclusive	Not Detected	Not Detected	Not Detected	Not Detected
Diameter change from 72 in. to 66 in. at 8.5 ft—rock socket	Not Detected	Not Detected	Not Detected	Not Detected	Not Detected	Not Detected
8 in. soil inclusion added at 14.0 ft concrete pumped 6 in. above soil inclusion	Detected	Detected	Detected	Detected	Detected	Detected
4 in. soil inclusion added at 20.0 ft concrete pumped 6 in. above soil inclusion	Detected	Detected	Detected	Detected	Detected	Detected

CHAPTER 6: TEST DRILLED SHAFT #3

INTRODUCTION

Test drilled shaft #3 is located 0.3 miles north of Nelson Road in Grundy County, Illinois, along IL-47. The location of test drilled shaft #3 is shown in Figure 132 of Appendix E. A detailed longitudinal profile of the initial design of test drilled shaft #3 is shown in Figure 26. In particular, Figure 26 shows the design of the drilled shaft with details of the temporary casings used, shaft diameter and length, and a rock socket. Figure 26 also shows the planned defects included in the test shaft, which include a soft toe and two tremie pipe raises during concrete placement. The main design parameters for test shaft #3 are a length of 40 ft, shaft diameter of 4 ft, rebar cage diameter of 3 ft, and a 4.5 ft diameter temporary casing to a depth of 3 ft.

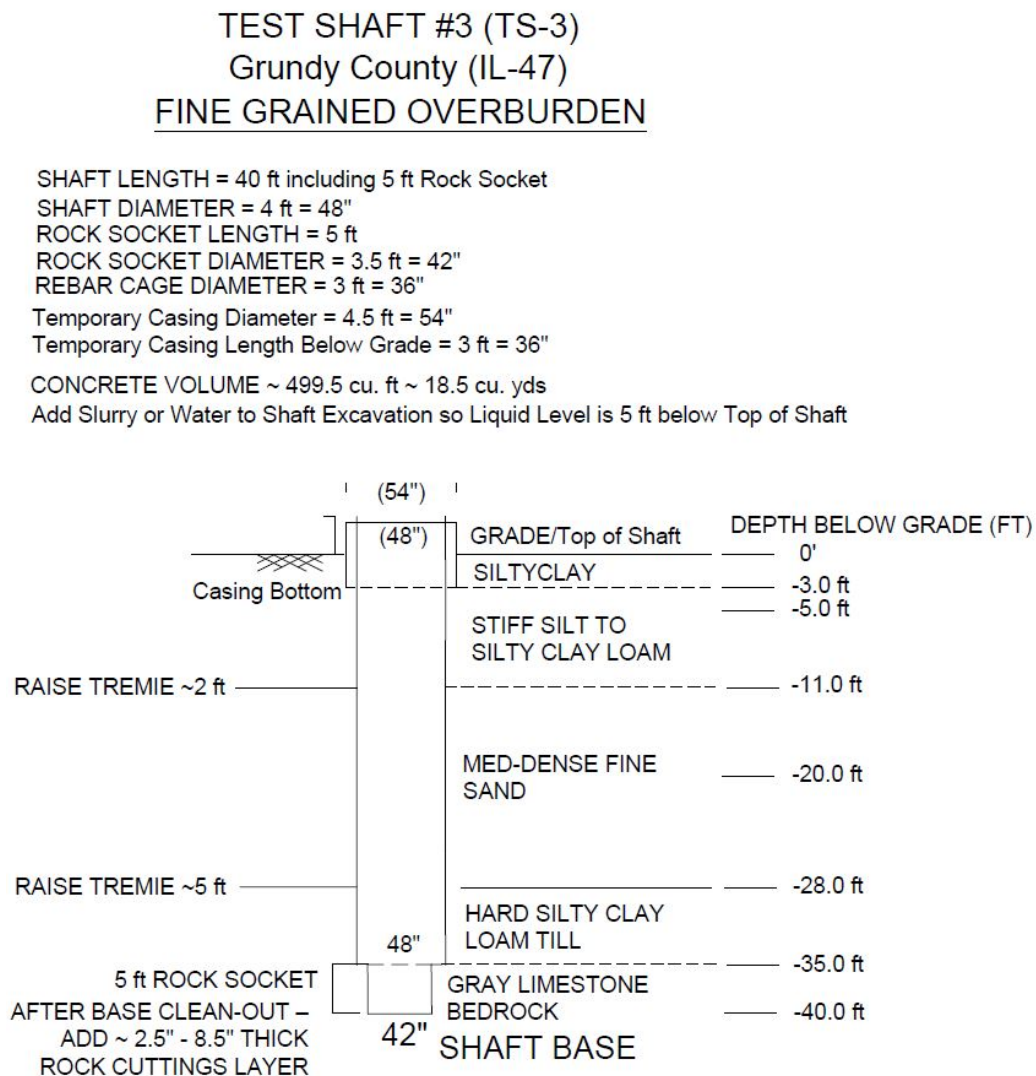


Figure 26. Illustration. Initial design of test drilled shaft #3 located 0.3 miles north of Nelson Road in Grundy County, Illinois, along IL-47.

A soft toe was created at the bottom of the drilled shaft at a depth of 40 ft. A soft toe means the bottom of the drilled shaft was not cleaned out, so soil or cuttings, or both, were left at the tip of the shaft or added to the bottom. Approximately 2.5 in. of soil was left at the tip of the shaft to assess the effectiveness of TIP and CSL testing in detecting this common condition. Concrete was poured for test shaft #3 following the wet method. The following defects or concrete placement variables were included in the construction process: a 2 ft tremie pipe raise above the top of the concrete surface with discharge of fresh concrete into the water at a depth of 11 ft and a 5 ft tremie pipe raise at a depth of 28 ft.

Figure 27 shows the design cross section of test drilled shaft #3, where the details of the rebar cage are shown. The outside diameter of the rebar cage is 3 ft, with a 7 in. clear distance between the longitudinal rebars that consist of 13 #8 vertical rebars and #6 hoops at 12 in. vertical spacing. Figure 27 also shows the four CSL steel access tubes installed inside the rebar cage (one per foot of shaft diameter). Each tube has an outside diameter of 2 in.

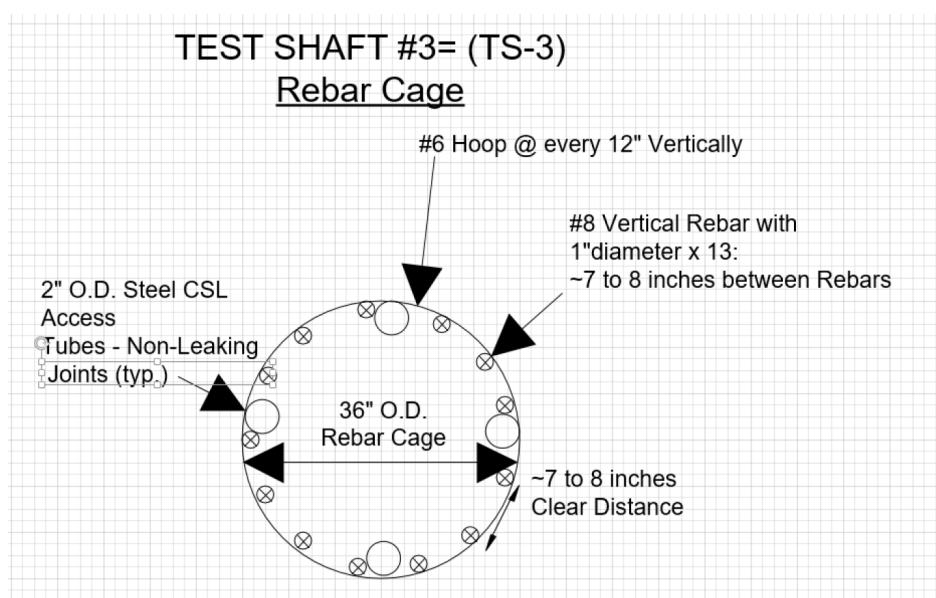


Figure 27. Illustration. Initial design cross section of test drilled shaft #3 with reinforcement detail.

TEST SHAFT #3 CONSTRUCTION

Test drilled shaft #3 was poured using the wet method on October 26, 2020, and the concrete was placed via a pump truck and tremie pipe. The reported placed concrete volume is 23 yd³. Drilled shaft information, soil boring logs, and installation details are shown in Appendix E. The rebar cage was instrumented with eight thermal wire cables (two per foot of shaft diameter) extending to the bottom of the cage. The wires are numbered clockwise, with wire 1 corresponding to the wire in the northeast position. Please see the TIP test logs (Figure 161) located in Appendix E for the location of each thermal wire. The temporary casing measured 4.5 ft in diameter and extended to a depth of 3 ft. After installing the 48" casing, it reached to a depth of 26 ft. The 48" auger could not be used to drill the soil beyond 26 ft after installing the 48" casing, and therefore, while the rock layer was not reached yet, the 42" auger was used to continue drilling through the hard silty clay loam till. The rock

layer was reached at a depth of 37 ft. Therefore, the diameter of the uncased section above the rock socket is 42" which is from a depth of 26 ft to 37 ft through a layer of hard silty clay loam. From a depth of 37 ft to the end of the shaft (depth 42.5 ft), there is another 4.5 ft rock socket with 42" diameter. Figure 161 in Appendix E shows a sketch of the TIP wire configuration, including wire-wire distances, the serial number for each wire, and general drilled shaft information. Figure 162 in Appendix E also shows a diagram of the typical access tube configuration, including CSL tube numbering and details of the CSL testing combination.

Figure 28(a) shows the installation of 4.5 ft outer diameter temporary casing, and Figure 28(b) shows the start of excavation for test drilled shaft #3. Figure 29 shows the 3 ft diameter rebar cage with four CSL access tubes and eight TIP thermal wires already installed or attached to the cage. Figure 30(a) shows the rebar cage before placement in the drilled shaft. Figure 30(b) shows the 3 ft diameter rebar cage with four CSL access tubes and eight TIP thermal wires after concrete pouring. Figure 31 shows the as-built diagram for test drilled shaft #3, which includes the pre-planned defects.



Figure 28. Photo. Photographs showing (a) start of excavation for test drilled shaft #3 and (b) installation of 4.5 ft diameter temporary casing.



Figure 29. Photo. Photograph showing 3 ft diameter rebar cage with four CSL tubes and eight TIP wires installed.



(a)

(b)

Figure 30. Photo. Photographs showing (a) suspended 3 ft diameter rebar cage with four CSL tubes and eight TIP thermal wires and (b) test drilled shaft #3 after concrete pouring.

**TEST SHAFT #3 (TS-3) -As built
Grundy County (IL-47)
FINE GRAINED OVERBURDEN**

SHAFT LENGTH = 41.5 ft including 4.5 ft Rock

Socket

SHAFT DIAMETER = 4 ft = 48"

ROCK SOCKET LENGTH = 4.5 ft

ROCK SOCKET DIAMETER = 3.5 ft = 42"

REBAR CAGE DIAMETER = 3 ft = 36"

Temporary Casing 1 Diameter = 4.5 ft = 54"

Temporary Casing 1 Length Below Grade = 3 ft = 36"

Temporary Casing 2 Diameter = 4 ft = 48"

Temporary Casing 2 Length Below Grade = 26.5 ft = 318"

CONCRETE VOLUME ~ 621 cu. ft ~ 23 cu. yds

Add Water to Shaft Excavation so Liquid Level is 31.7 ft below Ground Surface

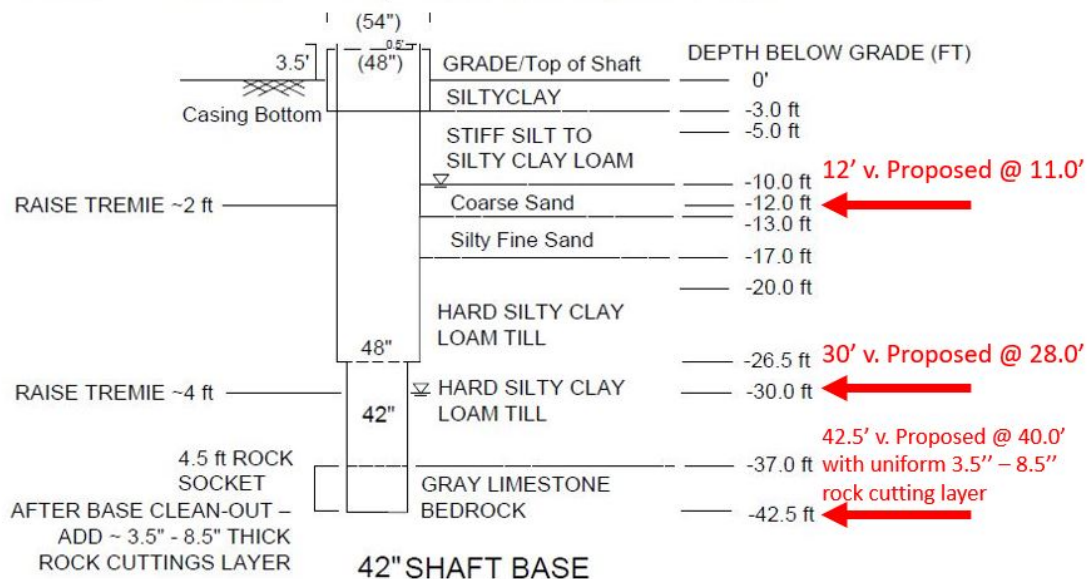


Figure 31. Illustration. As-built diagram for test drilled shaft #3.

Figure 31 shows that the actual length of the first casing below the ground surface is 3 ft, the second temporary casing was installed to a depth of 26.5 ft, the rock socket length is 4.5 ft, the first tremie pipe raise of 2 ft occurred at 12 ft, the second tremie pipe raise of 4 ft occurred at 30 ft, and the soft toe at the bottom of the drilled shaft is 3.5 in. to 8.5 in. thick at a depth of 42.5 ft. Furthermore, the drilled shaft has a diameter of 4 ft up to a depth of 26.5 ft and then changes to a diameter of 3.5 ft to the base of the drilled shaft at 42.5 ft deep.

TIP TESTING

The TIP data summarized in this chapter was recorded by Consultant A from October 26 through November 2, 2020. Similar to test drilled shaft #2, test drilled shaft #3 has twice the number of TIP wires than what is typically utilized (two thermal wires instead of one thermal wire per foot of drilled shaft diameter) as shown in Figure 161 of Appendix E. For test drilled shaft #3, eight thermal wire cables were attached approximately symmetrical around the rebar cage. The thermal wires extend the full length of the drilled shaft rebar cage. To identify localized defects within the test shaft, the following three analyses of the TIP data were conducted: (1) only considering odd-numbered wires, (2) only considering even-numbered wires, and (3) considering all the wires together. The odd-, even-, and all-wire analyses were independently examined by different individuals at Consultant A as well as the research team.

Temperature at Rebar Cage for Ideal Shaft

Similar to test drilled shafts #1 and #2, the temperature at the rebar cage that corresponds to an ideal drilled shaft with the same diameter as test drilled shaft #2 was investigated, and the results are summarized in Appendix E. Similar to drilled shafts #1 and #2, the predicted ideal temperatures conflict with each other, so Consultant A's evaluation method of the TIP testing data was adopted for evaluating the integrity of test drilled shaft #3. As previously mentioned, Consultant A assessed drilled shaft integrity using the TIP data by relating the overall average temperature for all thermal wires over the embedded depths to the overall volume of concrete installed. Consultant A's drilled shaft integrity assessment is based on the average temperature measurements from each thermal wire at each depth increment. If the measured average temperature versus depth is consistent, then the drilled shaft is considered of uniform shape and quality. Bulges can be identified as localized increases in average temperature, while insufficient concrete section or quality can be identified as localized decreases in average temperature.

Consultant A's TIP Results

Consultant A's interpretation of the thermal data for test drilled shaft #3 is presented in Appendix E. Test drilled shaft #3 achieved peak temperature approximately 23.5 hours after completion of concrete placement. The optimal time selected for the drilled shaft analysis usually occurs between time to one-half the time to peak temperature and the time at peak temperature. When anomalies are indicated in the thermal data, the analyses are normally performed closer to one-half the time to peak temperature when the temperature differences can have greater contrast.

Odd-Numbered Wires

Consultant A's radius analysis for the odd-numbered wires was performed near the time of one-half the time to peak temperature, or approximately 13 hours after placement (see Figure 32[a]). In Figure 32(a), the thermal wires are labeled 1 through 4, but these are the four odd-numbered wires, i.e., 1, 3, 5, and 7, installed in the rebar cage. Consultant A's interpretation of the thermal results shows the effective average radius is greater than the design radius of 24 in. in the cased section and 21 in. below the lower casing and in the rock socket. Based on the provided as-built drilled shaft geometry, the reported volume of placed concrete is 23 yd³, which is approximately 125% of the theoretical volume, which indicates some portions of the drilled shaft may be oversized. Temperature reductions near depths of 10 and 30 ft were observed by Consultant A. Consultant A's interpretation of the reduction indicated it is near a depth of 10 ft and is localized near wires 1 and 2 (see Figure 32[a]). The vertical extent of the reduction appears slightly greater near wire 2, because the reduction is observed from 9 to 10 ft.

The reduction observed by Consultant A near a depth of 30 ft is evident in all cable locations. As data from all cables show evidence of the reduction, the reduction was interpreted by Consultant A as a cross-sectional reduction in quality and not solely a concrete cover reduction of the rebar cage. Consultant A concluded a shifting in the reinforcing cage from a depth of 10 ft to the base of the drilled shaft occurred because wires 3 and 4 show lower temperatures, i.e., closer to the native soil/rock interface, and wires 1 and 2 show higher temperature, i.e., closer to the drilled shaft center, as shown in Figure 32(a).

Even-Numbered Wires

Consultant A's radius analysis using only the even-numbered wires was performed near the one-half the time to peak temperature, or approximately 13 hours after placement (see Figure 32[b]). In Figure 32(b), the thermal wires are labelled 1 through 4, but these are the four even-numbered wires, i.e., 2, 4, 6, and 8, installed in the rebar cage. Consultant A's TIP model for test drilled shaft #3 using data from only the even wires indicates a generally consistent drilled shaft profile. Given the oversized drilled shaft based on concrete volume, none of the observed effective radius reductions meet Consultant A's threshold for a defect. However, Consultant A does identify a significant inclusion at 30 ft below the top of the concrete in all four wires (see Figure 32[b]) because the temperature starts high and then decreases by the time one-half the time to peak temperature is achieved. This means this potential defect could affect most or all of the planned cross section of the shaft. This temperature increase is present at the start of testing, which is, according to Consultant A, a common observation with pre-planned defects that have been warmed by the sun prior to placement of the rebar cage in the drilled shaft.

A second location was observed to have an initial temperature increase, followed by a temperature reduction at one-half of the time to peak temperature. This anomaly was noted at 10 ft below the top of the drilled shaft. This starting elevated temperature was observed by Consultant A in even wires 1, 2, and 3, and the reduction in temperature is indicated in wire 2, as shown in Figure 32(b). Shifting of the rebar cage was also observed by Consultant A, with wire 4 being closer to the center of the shaft, i.e., higher temperature, and wire 2 being closer to the surrounding native soil, i.e., lower

temperature, in the upper 16 ft. Below approximately 12 ft, wire 1 is also closer to the center while wire 3 is closer to the surrounding native soil.

All Eight Thermal Wires

Consultant A's radius analysis for all the wires was approximately 16 hours after placement (see Figure 32[c]). Consultant A's TIP model from all eight thermal wires indicates the effective average radius is generally oversized relative to the casing diameter and as expected relative to the drill diameter. There is a reduction in temperature that Consultant A uses to conclude there is a reduction in the effective drilled shaft radius between 28 and 32 ft below the drilled shaft top. This temperature reduction is observable in all the wires but most strongly near wires 5, 6, and 7, as shown in Figure 32(c). Consultant A also found indications of a temperature reduction at a depth of 10 ft below the drilled shaft top near wires 3 and 4. The magnitude of the reduction by one-half the time to peak temperature would likely not be specifically identified or highlighted under normal analysis procedures. Consultant A also found indications of a slight shift of the rebar cage with wire 4 nearer the soil, i.e., lower temperature, and wire 7 near the drilled shaft center, i.e., higher temperature.

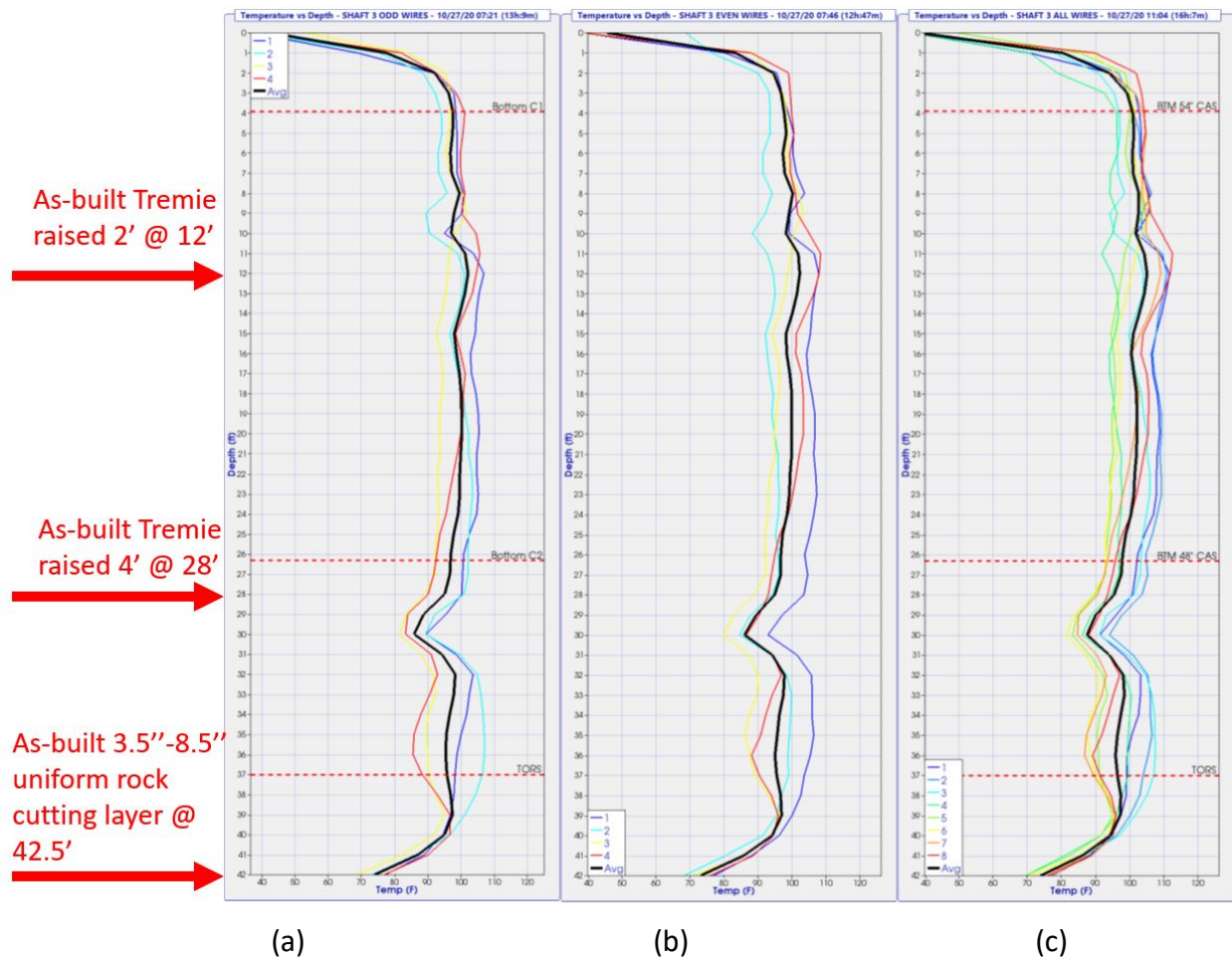


Figure 32. Graph. Temperature versus depth profile in test drilled shaft #3 for (a) the four odd wires at 13 hours and 9 minutes, (b) the four even wires at 12 hours and 47 minutes, and (c) all eight thermal wires at 16 hours and 7 minutes after concrete placement with red arrows showing defect locations.

UIUC's Interpretation of TIP Results

Table 13 presents a summary of the installed defects along with Consultant A's and UIUC's interpretation of the TIP data. A detailed discussion and analysis of the data from odd, even, and all wires performed by the research team is summarized in Appendix E. Nevertheless, it is important to note that using double the required number of thermal wires in TIP testing did not provide almost any additional insights to the integrity of the shaft. Therefore, there is no need to use more thermal wires than the required number of thermal wires (see Appendix F for IDOT specifications).

Table 13. Summary of TIP Data Interpretation by Consultant A and UIUC for Test Drilled Shaft #3

Pre-Planned Defect	Consultant A Interpretation (Odd-Numbered Wires)	Consultant A Interpretation (Even-Numbered Wires)	Consultant A Interpretation (All Wires)	UIUC Interpretation (All Wires)
2nd tremie pipe lift at ~12.0 ft mix-max free-fall ~2.0 ft	Detected at 10 ft	Detected at 10 ft	Detected at 10 ft	Detected at 10–11 ft
Cross section changed from 48 in. to 42 in. at 26.5 ft	Not Detected	Not Detected	Not Detected	Not Detected
1st tremie pipe lift at ~28.0 ft mix-max free-fall ~4.0 ft	Detected at 30 ft	Detected at 30 ft	Detected at 28–32 ft	Detected at 29–30 ft
3.5 in. to 8.5 in. thick soil inclusion added at 42.5 ft (base)	Not Detected	Not Detected	Not Detected	Not Detected

CSL TESTING

Consultant B performed CSL for test drilled shaft #3. CSL was performed in accordance with ASTM D6760 using the Cross-Hole Ultrasonic Module manufactured by Piletest.

Test drilled shaft #3 had concrete placement on October 26, 2020, and CSL testing was performed 18 days after on November 13, 2020. Test drilled shaft #3 contains four access tubes along the full length of the shaft for CSL. The access tubes consist of 2 in. diameter steel pipe in 10 ft long segments threaded together. Figure 162 of Appendix E presents the access tube arrangement for test drilled shaft #3. The initial CSL was performed on six combinations of access tubes. CSL measurements were taken along the length of the access tubes at 1 in. increment depth intervals.

For test drilled shaft #3, Consultant B claimed that one of the tubes (#2) was approximately 4 ft shorter than the other three tubes even though photographs show all the access tubes extended to the bottom of the rebar cage. In the field, Consultant B's depth measurements were all performed

based on the shallower (or higher elevation) tube bottom in access tube 2. As a result, the analysis by Consultant B was performed based on the shortest tube length. Unfortunately, this resulted in Consultant B not evaluating the lower 4 ft of the drilled shaft.

For test drilled shaft #3, the average height of steel access tube stickup above the top of concrete is approximately 3.8 ft at the time of CSL testing. The average steel access tube bottom elevation for the drilled shaft is 530 ft or a depth below ground surface of 42.5 ft. Based on the available data, the drilled shaft bottom elevation is at approximately 528.5 ft. The distance between the average bottom elevation of the access tubes and the estimated bottom elevation for the drilled shaft is approximately 1.5 ft.

A review of the drilled shaft installation logs in Appendix E for test drilled shaft #3 revealed the following observations:

- No significant deficiencies or irregularities were observed during concrete placement.
- An apparent concrete volume difference of 4.5 yd³ was observed between the apparent volume of concrete placed (23 yd³) and the theoretical concrete volume (18.5 yd³). This is an apparent concrete over-pour of approximately 24%. The theoretical concrete volume was determined from the various drilled shaft diameters and lengths provided. Similar to test shafts #2 and #3, one explanation is the apparent volume of concrete placed includes excess concrete that is pumped until it overflows the top of the casing as well as subtracting concrete that is left in the truck. It is sometimes difficult to quantify these amounts and should be considered an estimate only because the results may affect the amount of concrete over-pour calculated.

Consultant B's CSL Results

In general, Consultant B's interpretation of the CSL test results for test drilled shaft #3 show only minor deviations in FAT and relative energy in the tested tube combinations along the length of the drilled shaft. These minor fluctuations are less than 10% and therefore are considered insignificant. However, there are three exceptions within test drilled shaft #3 where zones of increased FATs and decreased relative energy were observed by Consultant B within a majority of the tested access tube combinations. A summary of the exceptions observed by Consultant B are presented in Table 14 along with their CCRC rating. In addition to the CCRC rating, Table 14 presents the concrete rating based on FHWA-NHI 18-024 (Brown et al., 2018).

Table 14. Consultant B’s Interpretation of CSL Data for Test Drilled Shaft #3

Depth Below Top of Shaft (ft)	Tube Combinations	CCRC Rating	2018 FHWA	Assessment
7 to 7.5	2–3	Questionable	Class B	Likely would not need additional evaluation
24.5 to 25.5	All	Poor/Defect	Class B / Class C	Likely defect/needs additional evaluation
35 to BOS	1–3, 2–3, 3–4	Questionable	Class B	Potential defect/needs additional evaluation

Based on Consultant B’s CSL testing and analysis and their review of the drilled shaft installation records shown in Appendix E, they concluded that test drilled shaft #3 contains at least three anomalies as previously outlined in Table 14 and are summarized below based on the following observations:

- Increased values of FAT and decreased relative energy in several areas with CCRC ratings ranging from Questionable to Poor/Defect (P/D).
- Several areas in test shaft #3 are classified as Class B and C according to Brown et al. (2018).
- No significant anomalies were observed in the remainder of CSL test results.
- Overall, test drilled shaft #3 has an average concrete quality rating of “Good,” as determined using the average apparent wave speed calculations near the drilled shaft top from the CSL data.

UIUC’s Interpretation of Consultant B’s CSL Results

Figure 33 and Figure 34 show the CSL testing performed on test drilled shaft #3 and used by the research team to assess the integrity of this shaft. Figure 33 and Figure 34 show a clear reduction in relative energy (see blue line) around 25 ft. The FAT profiles are not as indicative of the defect around 25 ft as the relative energy profiles, where in general, only a small increase in FAT values is observed around 25 ft. Class C (highly abnormal) is shown around 25 ft for profile 1–4 in Figure 33 as well as all profiles in Figure 34. The rest of the profiles around 25 ft show a Class B rating. No indication of any increase in FAT value is found around 12 ft, except for profile 2–3 in Figure 34 with a Class B (conditionally acceptable) rating. Furthermore, no significant or abnormal reduction in the apparent relative energy is found around 12 ft. No results are available from Consultant B beyond a depth of 36.1 ft, so the defect at the bottom of test drilled shaft #3 at 42.5 ft was not evaluated by Consultant B. The defect that was observed around a depth of 25 ft should be the 4 ft tremie pipe raise at 28 ft, which is the only defect that was detected by Consultant B using the CSL data. Table 15 presents a summary of the installed defects along with the interpretation of the CSL results by Consultant B and UIUC. There is good agreement between the Consultant B and UIUC interpretations shown in Table 15.

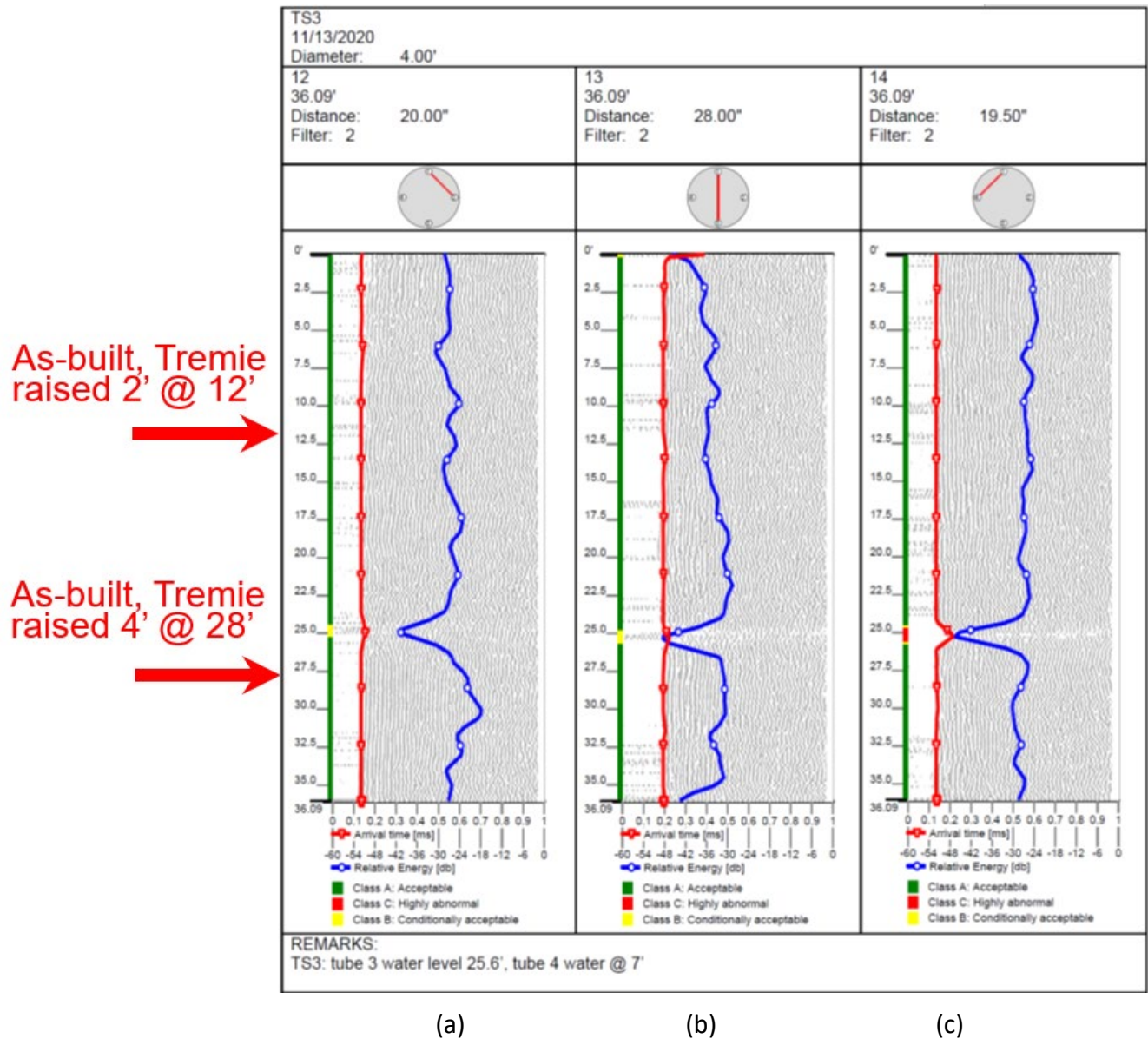


Figure 33. Graph. Consultant B's CSL results for test drilled shaft #3 for (a) along an edge of the shaft (profile 1-2), (b) across the shaft (profile 1-3), and (c) along an edge of the shaft (profile 1-4), with red arrows showing defect locations.

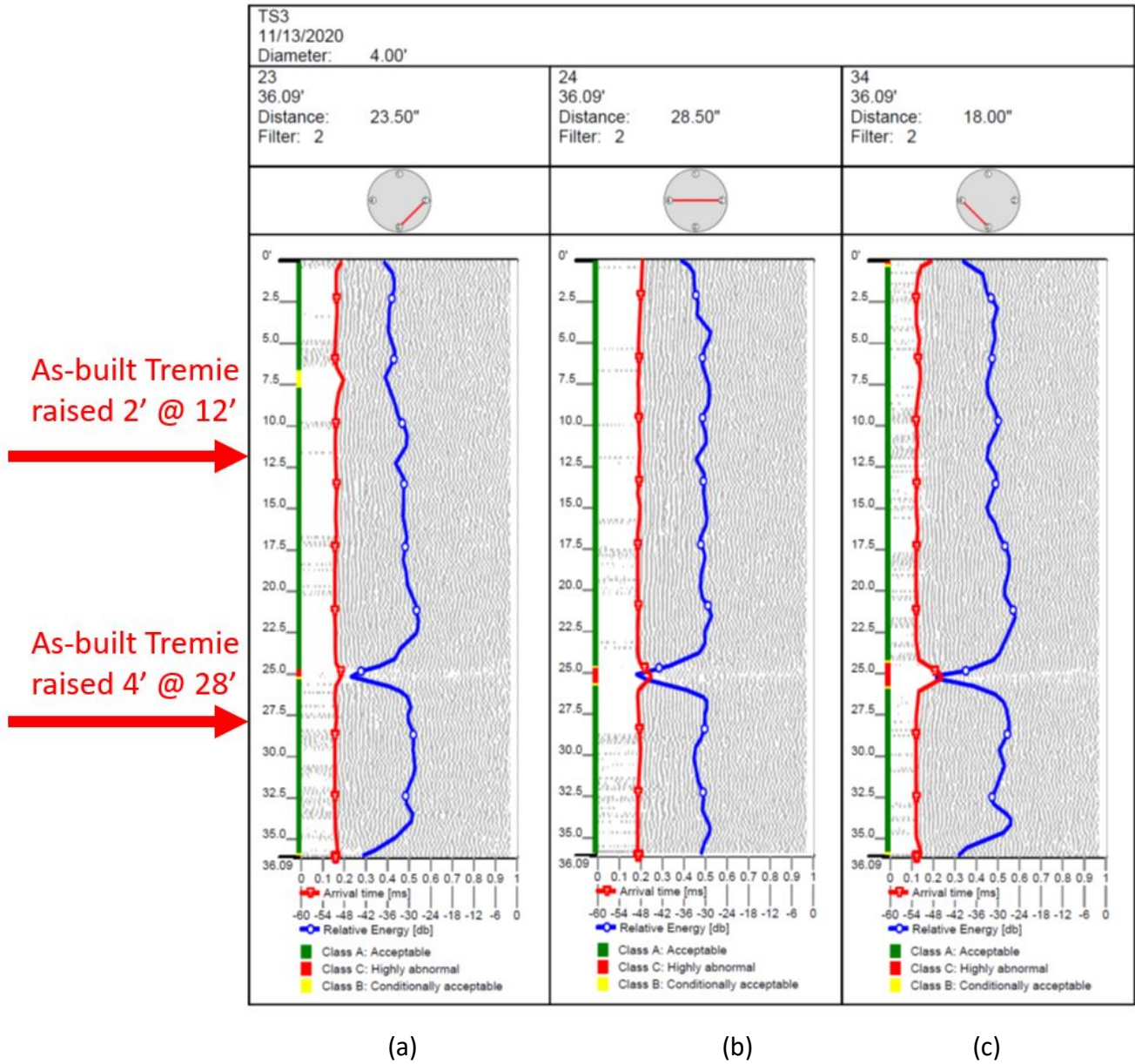


Figure 34. Graph. Consultant B's CSL results for shaft #3 for (a) along an edge of the shaft (profile 2–3), (b) across the shaft (profile 2–4), and (c) along an edge of the shaft (profile 3–4), with red arrows showing defect locations.

Table 15. Summary of CSL Interpretation by Consultant B and UIUC for Test Drilled Shaft #3

Defect	Consultant B Interpretation	UIUC Interpretation
Casing bottom at 3.0 ft	Not Detected	Not Detected
2nd tremie pipe lift at ~12.0 ft mix-max free-fall~2.0 ft	Not Detected	Not Detected
Cross section changed from 48 in. to 42 in. at 26.5 ft	Not Detected	Not Detected
1st tremie pipe lift at ~28.0 ft mix-max free-fall~4.0 ft	Detected at 25 ft	Detected at 25 ft
3.5 in. to 8.5 in. thick soil inclusion added at 42.5 ft (base)	No analysis beyond 36 ft	Not Detected

Consultant A's CSL Results

Consultant A was provided with the drilled shaft construction records for test drilled shafts #3, which are included in Appendix E. Consultant A also performed CSL on test drilled shaft #3 on November 5, 2020, or six days after its installation. For test drilled shaft #3, the steel access tubes are labeled 1 through 4 in a clockwise manner, with tube 1 corresponding to the first tube clockwise from due north for each drilled shaft, as shown in Appendix E. The CSL results are referred to as “profiles,” with profile 1–2 being the CSL results between the first and second access tubes clockwise from due north. Tests on four perimeter profiles and two diagonal profiles were performed by Consultant A for test drilled shaft #3. Consultant A performed their testing and analysis over the entire length of CSL access tubes (42.5 ft). In other words, Consultant A did not conclude that one of the access tubes (#2) was approximately 4 ft shorter than the other three tubes as Consultant B did.

At depths of 28.0 to 30.0 ft below the top of the concrete, all profiles are categorized as Class B or C by Consultant A, as shown in Figure 35, Figure 36, and Figure 37. Profile 1–4 is identified as Class B, with a FAT increase of 18% and an energy decrease of less than 9 dB. The remaining five profiles are identified as Class C quality concrete, with FAT increases from 19% to 100% and energy decreases from 9 dB to greater than 12 dB. Three profiles (1–2, 2–4, and 2–3) at a depth of 40 ft are categorized as Classes B, B, and C, respectively. Profiles 1–2 and 2–4 have FAT increases of 19% to 29% and energy decreases less than 9 dB. Profile 2–3 has FAT increases of 81% and energy decreases of 9 dB to 12 dB.

UIUC's Interpretation of Consultant A's CSL Results

Figure 35, Figure 36, and Figure 37 show the Consultant A test results of the CSL test performed on test drilled shaft #3. The figures show a reduction in the relative energy and an increase in FAT values around a depth of 29 ft, except for profile 1–4 in Figure 35, where the increase in FAT values is not as

large as in other profiles. None of the profiles show an obvious change in the FAT values or relative energy around 12 ft, which is the depth of a tremie pipe raise. This could be because the defect that was created at 28 ft is a 4 ft high tremie pipe raise, which is higher (4 ft) than the 2 ft high tremie pipe raise at 12 ft. In other words, a tremie pipe raise of only 2 ft may not be detectable with current CSL technology.

Profile 1–2 in Figure 35, profile 2–3 in Figure 36, and profile 2–4 in Figure 37 show an increase in FAT values and a decrease in the relative energy at the base of the drilled shaft, which is attributed to the soft toe that was installed.

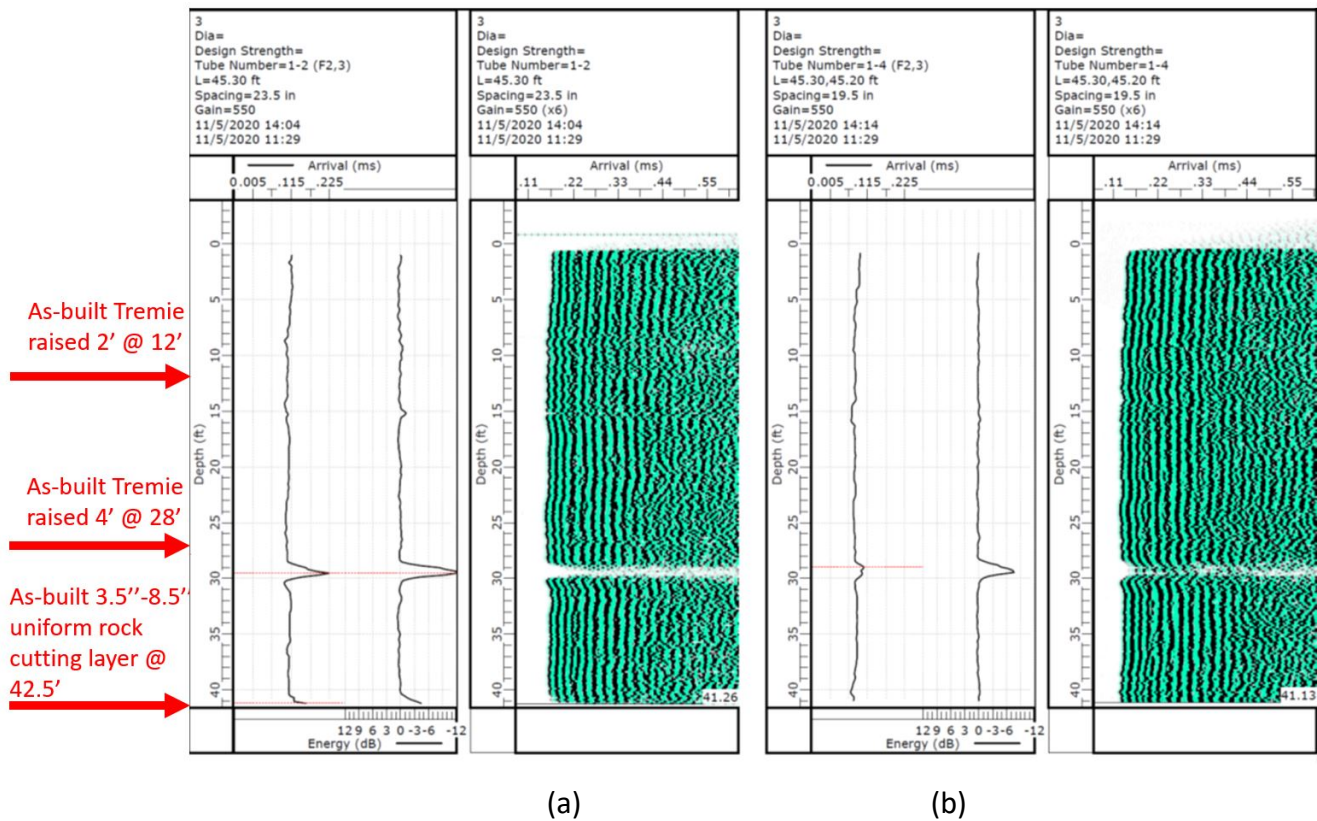


Figure 35. Graph. Consultant A's CSL results for test drilled shaft #3 for (a) profile 1–2 and (b) profile 1–4, with red arrows showing defect locations.

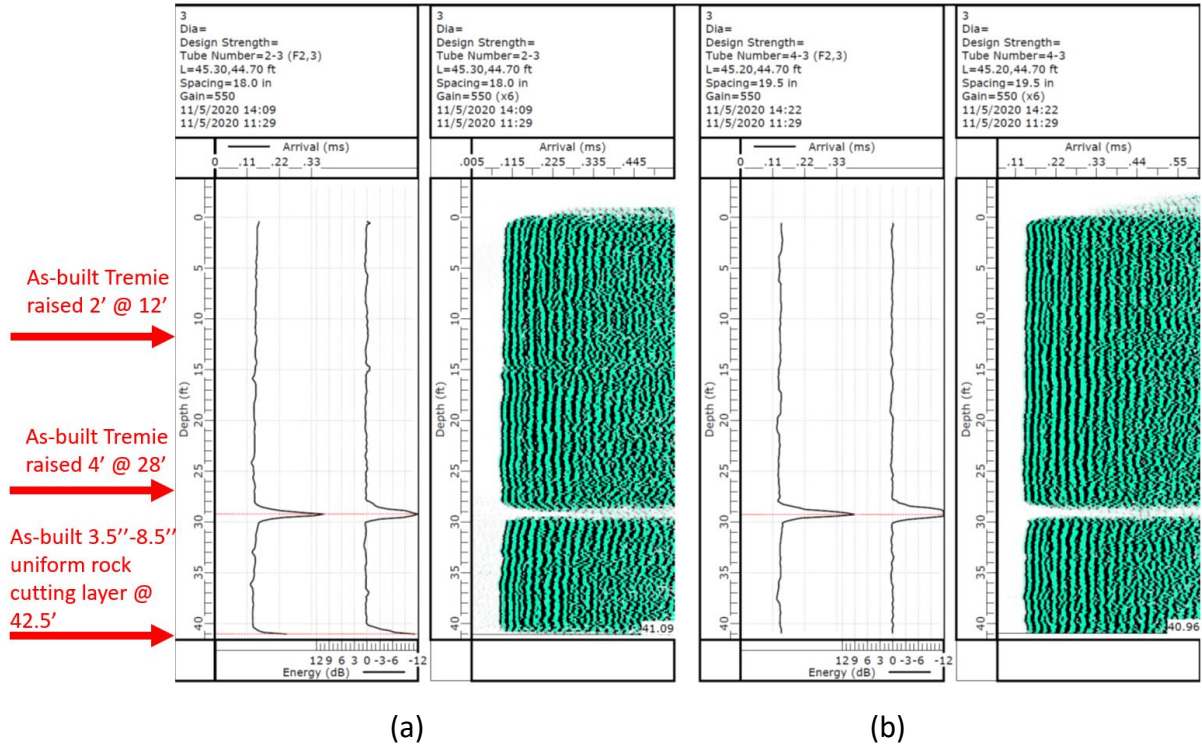


Figure 36. Graph. Consultant A's CSL results for test drilled shaft #3 for (a) profile 2-3 and (b) profile 4-3, with red arrows showing defect locations.

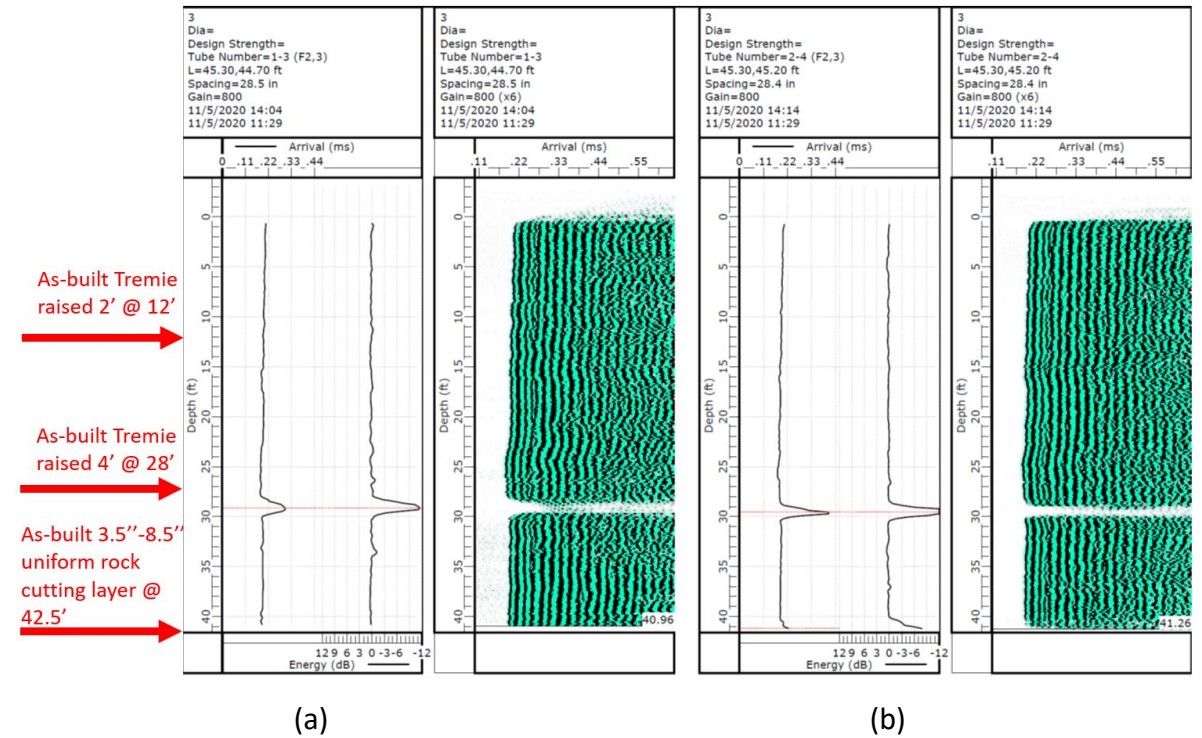


Figure 37. Graph. Consultant A's CSL results for test drilled shaft #3 for (a) profile 1-3 and (b) profile 2-4, with red arrows showing defect locations.

Table 16 shows a summary of the installed defects along with the interpretation of the CSL results by Consultant A and UIUC interpretation. Table 16 shows the only defects that were detected herein are the 4 ft tremie pipe raise at 28 ft and the 3.5 to 8.5 in. of soil at the soft toe.

Table 16. Summary of CSL Interpretation by Consultant A and UIUC for Test Drilled Shaft #3

Defect	Consultant A Interpretation	UIUC Interpretation
Casing bottom at 3.0 ft	Not Detected	Not Detected
2nd tremie pipe raise at ~12.0 ft mix-max free-fall ~2.0 ft	Not Detected	Not Detected
Cross section changed from 48 in. to 42 in. at 26.5 ft	Not Detected	Not Detected
1st tremie pipe raise at ~28.0 ft mix-max free-fall ~4.0 ft	Detected at 29 ft	Detected at 29 ft
3.5 in.–8.5 in. soil inclusion added at 42.5 ft (base)	Detected in Half of the Six Profiles	Not Detected

CORING OF TEST SHAFT #3

Two concrete cores were performed on test drilled shaft #3 with a core diameter of 2 in. The first coring was performed on April 14, 2021, and it was performed at the center of the drilled shaft and stopped at a depth of around 35 ft due to damage of the cutter head after encountering some rebar. The only defects observed by the first concrete coring above 35 ft are a joint observed at a 28.5 ft and 14 in. thick zone of bad concrete from a depth of 28.5 ft to 29 ft 8 in., which probably corresponds to the 4 ft tremie pipe raise at 28 ft. However, the first concrete coring did not reach the bottom of the drilled shaft, so it did not encounter the soft toe. Therefore, a second concrete core was performed on October 11, 2021, and was located closer to the rebar cage to investigate the bottom of the drilled shaft. Figure 155 in Appendix E shows the defect encountered in the first core.

Figure 38 shows the as-built diagram for the concrete coring of test drilled shaft #3. The photographs of the defects found while conducting the second concrete coring for test shaft #3 are shown in Appendix E. A joint was observed at a depth of 11 ft 9 in., and another defect was observed between a depth of 28 ft 7 in. and 29 ft 7 in. The second defect was observed in the field as gravel or broken-up concrete with a length of 12 in. The defect at 28 ft was detected by CSL, while the defect at 12 ft was not detected by CSL testing, which could be the joint observed in the second concrete coring at 11 ft 9 in. However, this joint could have been created during concrete coring and only indicates a weak concrete zone. Therefore, it will not have a great effect on the FAT values or the relative energy of the concrete as the second defect at a depth of 28 ft, which contains weak concrete that led to an increase in FAT values and reduced the relative energy.

TEST SHAFT #3 (TS-3) -As built
(Coring) Grundy County (IL-47)
FINE GRAINED OVERBURDEN

SHAFT LENGTH = 41.5 ft including 4.5 ft Rock
 Socket
 SHAFT DIAMETER = 4 ft = 48"
 ROCK SOCKET LENGTH = 4.5 ft
 ROCK SOCKET DIAMETER = 3.5 ft = 42"
 REBAR CAGE DIAMETER = 3 ft = 36"
 Temporary Casing 1 Diameter = 4.5 ft = 54"
 Temporary Casing 1 Length Below Grade = 3 ft = 36"
 Temporary Casing 2 Diameter = 4 ft = 48"
 Temporary Casing 2 Length Below Grade = 26.5 ft = 318"
 CONCRETE VOLUME ~ 621 cu. ft ~ 23 cu. yds
 Add Water to Shaft Excavation so Liquid Level is 31.7 ft below Ground Surface

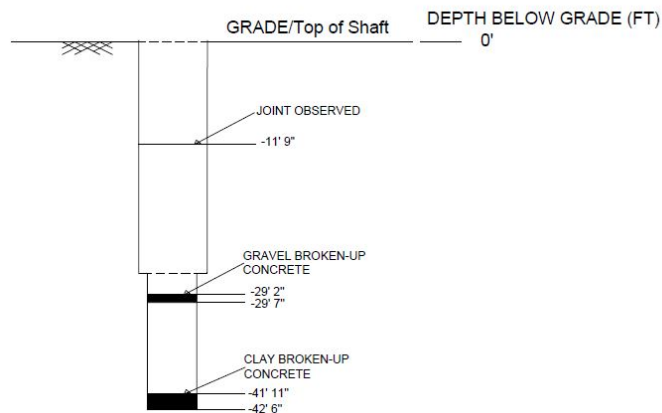


Figure 38. Illustration. As-built concrete coring of test drilled shaft #3.

The third defect was observed between a depth of 41 ft 11 in. and 42 ft 6 in. This defect was observed in the field as clay with some broken-up concrete having a length of 7 in. The soft toe defect at the bottom of the concrete has a thickness within the expected 3.5 to 8.5 in.

SUMMARY

This chapter discusses the construction and testing of test drilled shaft #3, which is located 0.3 miles north of Nelson Road in Grundy County, Illinois, along IL-47. In summary, TIP testing provided a better identification than CSL testing of the 2 ft high tremie pipe raise at 12 ft, which was not detected by CSL testing. Both TIP and CSL data predicted the 4 ft tremie pipe raise at 28 ft. The following paragraphs explain this conclusion.

The following defects were installed in the test shaft and then TIP testing, CSL testing, and concrete coring were performed to evaluate which integrity test better detected these pre-planned defects: (1) tremie pipe raise at a depth of 12 ft, (2) tremie pipe raise at 28 ft, and (3) soil added at the bottom of the shaft to create a soft toe. Test drilled shaft #3 has a length of 42.5 ft and a 4 ft diameter and was equipped with four CSL access tubes and eight TIP thermal wires. The test results were collected by Consultant A for TIP and CSL testing and by Consultant B CSL testing.

Table 17 shows a summary of the findings from Consultant A and the UIUC research team for TIP testing and from Consultant B, Consultant A, and UIUC for CSL testing. In particular, Table 17 shows

that TIP testing provided better identification than CSL testing of the 2 ft high tremie pipe raise at 12 ft, which was not detected by CSL testing. Both TIP and CSL data identified the 4 ft tremie pipe raise at 28 ft. However, TIP testing failed at identifying the defect at the base of the drilled shaft (soft toe) due to the temperature roll-off caused by the cooler native geologic materials, while the CSL data identified the defect at the base of the drilled shaft (soft toe). In summary, Table 17 shows that CSL testing is better than TIP testing at identifying the defects at the bottom of the drilled shaft. It is important to note that using double the required number of thermal wires in TIP testing did not provide almost any additional insights to the integrity of the shaft. Therefore, there is no need to use more thermal wires than the required number of thermal wires (see Appendix F for IDOT specifications). Furthermore, TIP testing and CSL testing from Consultant A found the defect at around 28 to 29 ft, which was confirmed by the concrete coring. Only CSL data from Contractor B identified a defect at 25 ft. Consultant B also claimed that one of the CSL tubes was 4 ft shorter than the other tubes and therefore did not perform analysis below 36 ft. However, Consultant A did perform CSL testing analysis up to a depth of 40 ft and did not mention anything about any of the tubes being short. Therefore, the defect identified by Consultant B at 25 ft from the CSL testing is not considered reliable as it did not agree with the concrete coring or TIP testing.

Similar to test drilled shaft #1, concrete coring of test drilled shaft #3 at the center of the shaft found only one defect, and therefore, integrity testing can provide better insight of drilled shaft quality than coring at the center of the shaft. However, all defects were detected by the second concrete coring performed near the rebar cage. Therefore, concrete coring near the rebar cage may be able to provide better results than coring at the middle of the drilled shaft

Table 17. Summary TIP Testing and CSL Score Card for Test Drilled Shaft #3

Defect	Data Interpretations					
	Consultant A's TIP (All wires)	UIUC's TIP (All wires)	Consultant A's CSL	UIUC's CSL	Consultant B's CSL	UIUC's CSL
Casing bottom at 3.0 ft	Not Detected	Not Detected	Not Detected	Not Detected	Not Detected	Not Detected
2 ft tremie pipe raise at ~12.0 ft	Detected at 10 ft	Detected at 10–11 ft	Not Detected	Not Detected	Not Detected	Not Detected
Cross section changed from 48 to 42 in. at 26.5 ft	Not Detected	Not Detected	Not Detected	Not Detected	Not Detected	Not Detected
4 ft tremie pipe raise at ~28.0 ft	Detected at 28–32 ft	Detected at 29–30 ft	Detected at 29 ft	Detected at 29 ft from Consultant A results	Detected at 25 ft	Detected at 25 ft
3.5 in. to 8.5 in. thick soil inclusion added at 42.5 ft (base)	Not Detected	Not Detected	Detected in half of the six profiles	Detected from Consultant A results	No analysis beyond 36 ft	No analysis beyond 36 ft

CHAPTER 7: SUMMARY AND CONCLUSIONS

This research project involved constructing three test drilled shafts at three locations in Illinois with different lengths, diameters, and planned defects. The defects were selected to cover most of the defects expected to occur during the construction of drilled shafts in Illinois. The defects include tremie pipe raises out of the poured concrete, soil inclusion in the drilled shaft, and soil at the bottom of the drilled shaft. Table 18 shows a summary of the test drilled shafts constructed during this project. TIP testing, CSL testing, and concrete coring were performed on all test drilled shafts. Table 19 shows a summary of the TIP and CSL testing results for the three test drilled shafts. It is important to note that using double the required number of thermal wires in TIP testing did not provide any additional insights to the integrity of the shaft. Therefore, there is no need to use more than one thermal wire per foot of shaft diameter (see Appendix F for IDOT Standards).

Table 18. Summary of Test Drilled Shaft Details

Test Drilled Shaft No.	Drilled Shaft Diameter (ft)	Cage Diameter (ft)	Drilled Shaft Length (ft)	Soil Depth (ft)	Rock Socket Depth (ft)	Drilling Fluid Used	No. of TIP Wires	No. of CSL Tubes
1	4	3.5	50	50	0	Wet	4	4
2	6 and 5.5 in rock	5	25	8	17	Dry	12 (2x Shaft Diameter)	6
3	4 and 3.5 in rock	3	42.5	37	5.5	Wet	8 (2x Shaft Diameter)	4

Table 19. Summary of TIP and CSL Testing Results

Test Drilled Shaft No.	Defect #1	How Detected	Defect #2	How Detected	Defect #3	How Detected	Defect #4	How Detected
1	Soil inclusion at bottom	CSL & TIP	3.5 ft tremie pipe raise	CSL (inconclusive)	1.5 ft tremie pipe raise	Not detected		
2	Thin soil inclusion at bottom	CSL & TIP	Thick soil inclusion	CSL & TIP	1.5 ft tremie pipe raise	TIP	Soil in annulus	TIP
3	Soil inclusion at bottom	CSL	4.0 ft tremie pipe raise	TIP & CSL	2.0 ft tremie pipe raise	TIP		

A summary of the strengths and weaknesses of TIP and CSL testing is presented on the next page.

TIP Strengths

- TIP testing is effective at identifying defects resulting from large tremie pipe raises in wet drilled shaft construction.
- TIP testing is somewhat effective at assessing rebar cage concrete cover for side resistance evaluation.
- TIP testing is effective at identifying soil inclusions that encroach inside rebar cage.
- TIP results can be available within two days of concrete pouring.

TIP Weaknesses

- Due to temperature decrease or roll-off at the top and bottom of the drilled shaft, TIP is not as effective at identifying anomalies near the top and bottom of shafts.
- TIP testing provides limited information at the center of large diameter drilled shafts.
- A shaft extending into a river with flowing water around the casing may influence temperature results and make it hard to identify defects, and therefore, a numerical analysis might be needed for this or other special cases.

CSL Strengths

- CSL testing is effective at assessing the condition at the drilled shaft bottom. For example, it can identify uncleaned rock socket.
- CSL testing is effective at assessing the concrete at the center of the drilled shaft inside the surrounding rebar cage.
- CSL testing is effective at identifying soil inclusions and voids in the drilled shaft center.
- CSL testing is effective at identifying defects resulting from large tremie pipe raises in wet drilled shaft construction.
- CSL tests can be repeated on the same shaft if necessary to verify results, investigate anomalies further using offset tomography, or to verify post-remediation improvements.

CSL Weaknesses

- CSL tubes might be damaged due to bending during lifting of long rebar cages and insertion into the drilled shaft, which could allow concrete inside the CSL tubes, preventing the CSL equipment from accessing the full length of the drilled shaft. Therefore, personnel must ensure access tube joints are securely sealed during cage insertion, and access tube joints may need to be replaced if they are damaged.

- CSL testing does not provide information about concrete cover outside the rebar or rebar cage misalignment.
- CSL testing is typically performed three to seven days after concrete pouring and is typically done no later than 21 days. The longer the time, the more chance of tube debonding in the upper tube areas due to bumping of the tubes or large temperature swings. Therefore, reviewer should consider this if anomalies show up near the top of shaft. Nevertheless, CSL can be done even after 21 days, if needed, as long as tube debonding is considered during analysis of the data.

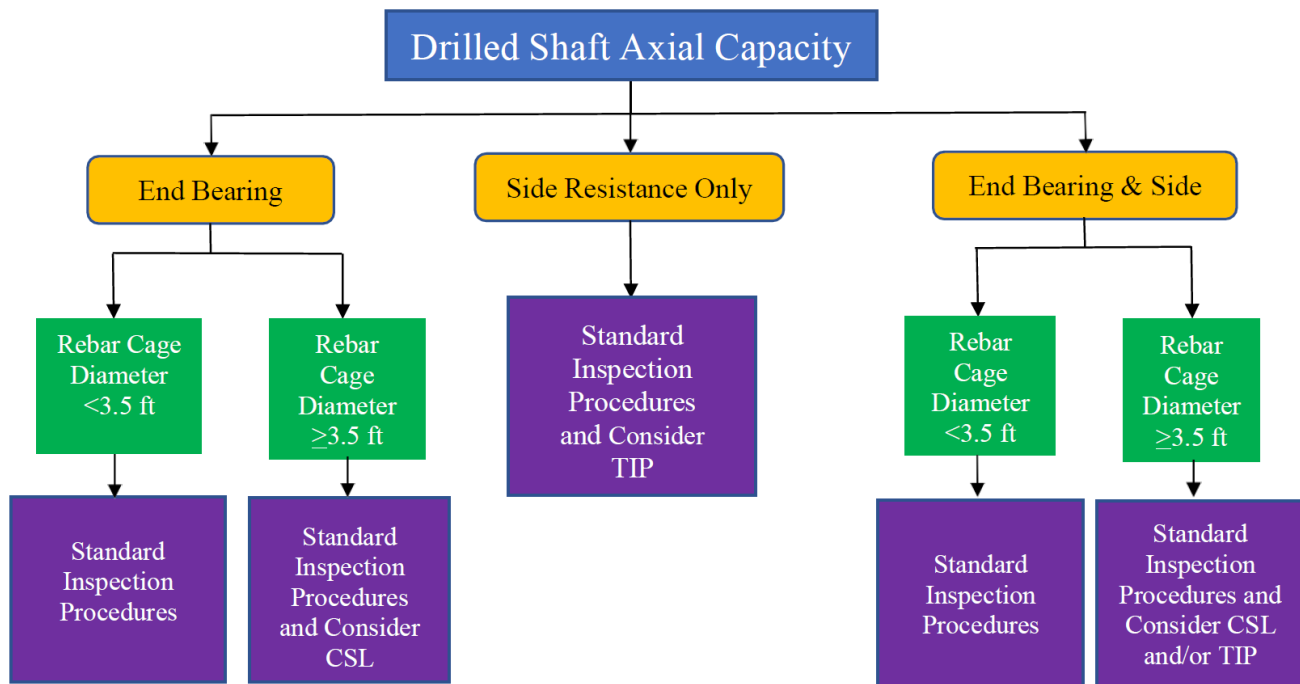
It is important to note that the TIP temperature drops at the tremie lift locations are often interpreted in the TIP reports as a loss of cover and/or narrowing of the shaft diameter which is not what is actually happening. The tremie lifts were intended to create a flaw across the entire cross section of the shaft at that location and would not cause a reduction in the diameter.

Concrete cores are usually drilled near the center of the drilled shaft, which could lead to missing some of the defects described above. It is recommended that coring be drilled near the rebar cage, as defects are likely to be present near the annulus of the drilled shaft just outside of the rebar cage (e.g., slough created during cage insertion, concrete pouring, and tremie pipe raises) because concrete is usually placed near the center of the drilled shaft. Therefore, the probability of a defect to occur is greater at the outer regions of the shaft than at the center due to the center placement and outward flow of the fresh concrete. The research team found that sometimes TIP and CSL testing are better at detecting defects than coring, because TIP and CSL test larger volumes of concrete than concrete cores. Furthermore, concrete cores may experience damage during extrusion from the core barrel, as is the case in the first core obtained on test drilled shaft #3. However, insertion of an optical/acoustical televiewer (not part of this study) down a core hole could be used to obtain a 360-degree view of the core walls to verify the presence of defects in the drilled shaft at the location of the core.

DECISION FLOWCHART

The scope of this research project includes development of guidelines that help identify the appropriate use of integrity testing considering project size, construction method, drilled shaft size, and design redundancy. This includes a simple flowchart developed for designers to determine which integrity testing method may be suitable for a certain type of drilled shaft.

After discussing the results of the TIP and CSL testing performed on three test drilled shafts with different lengths, diameters, and planned defects, this chapter discusses the criteria for selecting TIP and CSL testing for drilled shafts. The decision flowchart shown in Figure 39 was developed by the research team to be used as a guide by selecting integrity testing to be considered based on the general design capacity (i.e., end bearing, end bearing and side, or only side resistance) and on the diameter of the drilled shaft. Please note that users should use engineering judgement to make a final decision on CSL and TIP testing.



Note: This flowchart is a guide, and users should use engineering judgement to make a final decision on TIP or CSL requirements.

Figure 39. Chart. Bridge drilled shaft testing flowchart for selecting integrity testing for drilled shafts in Illinois.

Standard inspection procedures are still recommended for all cases because they are reliable, low cost, and can be performed in a short time. As a general guide, for drilled shafts designed to be end-bearing or end-bearing and side-resistance, with a rebar cage less than or equal to 3.5 ft, it is recommended to use only standard inspection procedures. This is because smaller drilled shafts tend to be for smaller bridges, and therefore, would carry smaller loads. Because of the smaller loads these drilled shafts carry, it would have lower risks associated with its integrity compared to larger shafts (cage diameter larger than 3.5 ft) that carry larger loads. However, the 3.5 ft is not a fixed number, and as previously mentioned, users should use engineering judgement to make a final decision on CSL and TIP testing. Therefore, the engineer can choose to use CSL and/or TIP testing for smaller drilled shafts if necessary. When the drilled shaft has a rebar cage larger than 3.5 ft and is an end-bearing drilled shaft, CSL testing should be considered due to the importance of detecting defects at the bottom of the drilled shaft. This research shows that CSL is better at detecting defects at the drilled shaft bottom than TIP testing due to issues with temperature roll-off.

If the drilled shaft has a rebar cage with a diameter greater than 3.5 ft and is designed for end bearing and side resistance, then TIP and/or CSL testing should be considered, since TIP testing can detect defects along the sides of the drilled shaft, and CSL testing can better detect problems with the drilled shaft bottom. For drilled shafts designed for resistance only, consideration of TIP testing is recommended since TIP testing can detect defects along the side of the drilled shaft.

The decision flowchart summarizes this guidance and can be used as a general guide for selecting the appropriate integrity testing based on the method of drilled shaft support and size of the drilled shaft. There are many more factors that could be considered in the selection criteria for integrity testing of a drilled shafts including: the structure type, structural and foundation redundancy, wet or dry construction conditions or methods, if permanent casing exists, and drilled shaft geometry.

UPDATED IDOT SPECIFICATIONS AND INSPECTOR CHECKLIST

Appendix F presents a recommended modified IDOT specification for TIP testing, and Appendix G presents a recommended modified IDOT specification for CSL testing. The specifying design engineer of record and the owner should determine if shaft integrity testing is to be employed, and which method(s) should be used at a particular structure, or substructure location within a structure. These specifications call for thermal sensors and access ducts for TIP and CSL testing, respectively, to be installed on all drilled shafts identified on the plans such that each shaft has the potential to be tested and analyzed. The design engineer shall also separately specify the minimum number of shaft tests/reports to be performed at each particular structure or substructure location. During construction, the owner's inspecting engineer will determine which specific drilled shafts shall have testing, analysis, and reporting performed on them. Based on field observations and results of the analysis, the engineer may direct additional tests to investigate problems encountered or observed during drilled shaft construction.

Based on the literature review, it is recommended that TIP data should be analyzed, and reported at one-half the time to peak temperature and at peak temperature of the concrete. The temperatures at one-half the time to peak temperature are used because the largest temperature differences occur roughly at one-half the time to peak temperature. The temperatures at one-half of the time to peak temperature are reviewed because this data becomes reliable and predictive as the temperature increases a significant amount above background or initial temperatures (Boeckmann & Loehr, 2018).

Appendix H presents a recommended modified IDOT Construction Inspector's checklist for drilled shafts. The modifications present additional items that the inspector should check during construction when TIP and CSL testing is specified for the drilled shaft.

FUTURE RESEARCH

The following topics are potential topics for future research on the nondestructive testing of drilled shafts:

- Interpreting TIP data is usually accomplished by discerning the general trend of shaft temperatures with depth. It would be helpful if there was a simple method of accurately predicting the concrete temperature of a drilled shaft as the hydration process progresses. This would allow for the measured temperatures to be compared to the predicted temperatures as a method to identify defects in the drilled shaft.
- TIP results cannot identify defects at the bottom of a drilled shaft due to temperature decreases or roll-off because of the lower temperature geologic material. Therefore, future

research should investigate temperature roll-off at the bottom of a drilled shaft to develop guidelines for the expected roll-off temperatures and curvatures that correspond to a clean drilled shaft bottom.

- The time at which TIP data should be interpreted should also be investigated numerically to improve interpretation techniques and interpretation repeatability.

REFERENCES

- Alabama Department of Transportation (ADOT). (2007). "Specifications for Drilled Shaft Construction." Section 506.10(a).
- Amir, J. M., Amir, E. I., & Felice, C. W. (2004). "Acceptance criteria for bored piles by ultrasonic testing." Proc., Int. Conf. on Application of Stress Wave Theory to Piling, Kuala Lumpur.
- ASTM Standard D6760. (2016). "Standard test method for integrity testing of concrete deep foundations by ultrasonic crosshole testing." American Society for Testing and Materials, Philadelphia, PA, Construction Vol. 4:09.
- ASTM D7949-14. "Standard Test Methods for Thermal Integrity Profiling of Concrete Deep Foundations." American Society for Testing and Materials, Philadelphia, Construction Vol. 4:09
- Brent, R. (2012). "Non-Destructive Testing of Drilled Shafts Current Practices and New Methods." Presentation, Pile Dynamics, Inc. Retrieved from: <https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1130&context=roadschool>
- Boeckmann, A., & Loehr, E.J. (2018). *Thermal integrity profiling for detecting flaws in drilled shafts* (Report No. WisDOT ID 0092-16-07). <https://wisconsindot.gov/documents2/research/0092-16-07-final-report.pdf>
- Broeckmann, A. Z., & Loehr, E. J. (2015). Concrete Mass Pours for Deep Foundations—Synthesis Report. Final Phase I Report to Federal Highway Administration.
- Brown, D. A., Turner, J. P., & Castelli, R. J. (2010). *Drilled shafts: Construction procedures, and LRFD design methods* (Report No. FHWA NHI-10-016). <https://www.fhwa.dot.gov/engineering/geotech/foundations/nhi10016/nhi10016.pdf>
- Deep Foundations Institute. (2005). *Manual for non-destructive testing and evaluation of drilled shafts*. John Wiley & Sons Ltd.
- Ferraro, C. (2003). *Advanced nondestructive monitoring and evaluation of damage in concrete materials*. Master of Civil Engineering Thesis, University of Florida.
- Harrell, S., & Stokoe, K. H. (1984). *Integrity evaluation of drilled piers by stress waves* (Report No. 2751F). Transportation Research Center, The University of Texas at Austin.
- Hyatt, T., Belardo, D., & Webster, J. (2019). Cost and technical comparison of non-destructive test methods for drilled shafts. In DFI 44th Annual Conference on Deep Foundations.
- Illinois Department of Transportation. (IDOT). (2019). "Crosshole Sonic Logging Testing of Drilled Shafts," Document GBSP91 revised 9 August 2019 and available at: <http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/GBSP91.pdf>.
- Liebich, B. A. (2004). "Acceptance Testing of Drilled Shafts by Gamma-Gamma Logging." Proceedings of GeoTrans 2004 Specialty Conference, Los Angeles, CA, ASCE, 1200–1208, [https://doi.org/10.1061/40744\(154\)109](https://doi.org/10.1061/40744(154)109).
- Malhotra, V. M. (1976). *Testing hardened concrete: Nondestructive methods*. American Concrete

Institute Monograph No. 9, ACI/Iowa State University Press.

- Moghaddam, R., Hannigan, P., & Anderson, K. (2018). Quantitative assessment of drilled shafts base-cleanliness using the shaft quantitative inspection device (SQUID). International Foundations Congress and Equipment Exposition, Orlando, Florida.
- Mullins, G. (1997). Advancements in drilled shaft construction, design, and quality assurance: The value of research. *International Journal of Pavement Research and Technology*, 6(2), 93–99, [https://doi.org/10.6135/ijprt.org.tw/2013.6\(2\)](https://doi.org/10.6135/ijprt.org.tw/2013.6(2))
- Mullins, G. (2010). Thermal integrity profiling of drilled shafts. *Journal of the Deep Foundations Institute*, 4(2), 54–64.
- Mullins, G., & Winters, D. (2011). *Infrared Thermal Integrity Testing Quality Assurance Test Method to Detect Drilled Shaft Defects* (Report No. WA-RD 770.1). <https://www.wsdot.wa.gov/research/reports/fullreports/770.1.pdf>.
- Mullins, G., & Kranc, S. (2007). *Thermal integrity testing of drilled shaft—final report* (Report No. #BD544-20). https://www.pile.com/wp-content/uploads/2017/03/FDOT_BD544_20_rpt.pdf

APPENDIX A: LITERATURE REVIEW

INTRODUCTION

Nondestructive integrity tests were originally developed as a quality assurance tool for precast driven piles and foundations constructed using construction techniques where portions of the construction could not be visually inspected, which is commonly referred to as “blind” construction. This testing is used because driving concrete piles can result in damage to the pile even though the pile was factory fabricated and inspected before shipment to the project. Conversely, drilled shafts are constructed on-site so all of the inspection and testing must be conducted during and after field construction.

In drilled shaft construction, the presence of drilling slurry or water prevents visual inspection of the shaft bottom, sidewalls, reinforcing bars, and concrete placement. Even without drilling slurry or water, visual inspection of the shaft bottom, sidewalls, and concrete placement is difficult. The blind nature of drilled shaft construction, especially under slurry or water, leads to uncertainties related to whether or not the constructed foundation element will perform as the designer intended. No single integrity testing method, destructive or nondestructive, can provide complete information on the integrity of a drilled shaft foundation. As a result, drilled shaft foundation projects commonly require careful construction, close inspection, and may also include the use of one or more types of integrity testing methods. For example, it is common in California to perform both Gamma-Gamma Logging and Crosshole Sonic Logging to evaluate the integrity of the concrete cover over the reinforcing steel cage and the concrete inside of the reinforcing steel cage, respectively, for drilled shaft construction.

This literature review addresses the means, methods, equipment, basic analyses, and the key advantages and limitations for the most commonly used integrity testing methods for drilled shaft construction to provide background information for the Illinois DOT research project. Listed in order of appearance in this chapter, the integrity methods discussed herein are: Crosshole Sonic Logging (CSL), Sonic Echo Testing (SET), Impulse Response Testing (IRT), Gamma-Gamma Logging (GGL), Concreteoscopy (CT), Parallel Seismic Integrity Testing (PSIT), and Thermal Integrity Profiling (TIP). This chapter ends with a summary focusing on CSL and TIP testing because these methods are commonly used on IDOT projects.

CROSSHOLE SONIC LOGGING (CSL)

CSL is probably the most well-established drilled shaft integrity testing method (ADOT, 2007; Mullins and Kranc, 2007). CSL testing involves the measurement of the compression wave velocity ($V_{p\text{-wave}}$) on horizontal planes at regular depths along the drilled shaft. The CSL access ducts, i.e., open steel or plastic access ducts (tubes) or pipes, are installed inside the reinforcing cage and the testing is used to assess concrete quality between the access ducts, i.e., inside the reinforcing cage, based on the measured compression wave velocity, first arrival time, and relative energy or signal intensity as discussed below.

CSL testing provides information on the uniformity and continuity of shaft concrete by computing the arrival time between signal emission and excitation of the nearby receiver. With a known distance travelled and measuring the arrival time allows for the calculation of the compression wave velocity ($V_{p\text{-wave}}$). The range of $V_{p\text{-wave}}$ for excellent to poor quality concrete is approximately 13,000 ft per second (4,300 m/s) and 6,700 ft per second (2,000 m/s), respectively (Mullins and Kranc, 2007). Slow arrival times are associated with low concrete density and strength.

The CSL test is usually performed in accordance with ASTM test method D6760, which leaves shaft acceptance to engineering judgment and the engineer of record.

The CSL test involves placing a seismic or ultrasonic source in one of the access ducts and signal receivers in at least one (1) of the other access tubes. For the testing conducted on the three (3) test shafts constructed as part of this project, an ultrasonic source was used. In general, the arrival time of the compression wave (p-wave) from the seismic or ultrasonic source is related to the density or unit weight of the concrete. If the concrete inside of the reinforcing cage is solid, free of discontinuities, and of good quality, the $V_{p\text{-wave}}$ is constant with depth at 12,000 to 13,000 ft/s (3,660 to 3,965 m/s). CSL is popular because there is a relatively simple and sound physical basis for the interpretation of test data and the test is relatively easy to perform after placement of the access ducts inside the reinforcing cage (Mullins and Kranc, 2007; ASTM D6760). The $V_{p\text{-wave}}$ for homogeneous, good quality concrete is related to Young's modulus (E), bulk unit weight (γ), and gravitational acceleration (g) as follows (Paikowsky et al., 2000):

$$V_{p\text{-wave}} = \sqrt{\frac{E^* g}{\gamma}}$$

If the concrete is compromised, the wave speed will be slower than 12,000 to 13,000 ft/s (3,660 to 3,965 m/s), which is the typical speed for good quality concrete. Because the distance between the access ducts (L) is known, $V_{p\text{-wave}}$ of the installed concrete between these two access ducts can be calculated using the arrival time (t) and the following expression:

$$V_{p\text{-wave}} = \frac{L}{t}$$

The Federal Highway Administration (FHWA) developed a Concrete Condition Rating Criteria (CCRC) based on the reduction in $V_{p\text{-wave}}$ from 12,000 to 13,000 ft/s (3,660 to 3,965 m/s) (Brown et al., 2018). For example, Table 20 relates the CRCC to the reduction in $V_{p\text{-wave}}$ to a quality symbol representing the concrete integrity. Table 20 shows that a decrease in $V_{p\text{-wave}}$ of less than 10% corresponds to good quality concrete.

Table 20. Concrete Condition Rating Criteria (CCRC) from FHWA (Brown et al., 2018)

Rating	Symbol	Apparent Wave Speed Reduction	Remarks
Good	G	<10%	Good quality concrete
Questionable	Q	10%–25%	Minor contamination or intrusion and/or questionable concrete quality
Poor/Defect	P/D	>25%	Results indicative of water slurry contamination or soil intrusion and/or poor quality concrete
No Signal	NS	No Signal	Highly probable that a soil intrusion or other severe defect has absorbed the signal
Water	W	C = 4750 to 5000 ft/sec	Indicative of a water intrusion or of water-filled gravel intrusion with few or no fines present

The First Arrival Time (FAT) is the time required for the first compression wave to reach the receiver probe from an access duct. As concrete quality increases, FAT decreases because good quality concrete can transmit the compression wave quicker than poor quality concrete or concrete contaminated with soil. As a result, an increase in FAT can be related to the percent decrease in V_{p-wave} as shown in Table 21 from DFI (2019). The empirical relationship in Table 21 can then be used with Table 20 to rate the quality of concrete. An anomaly is defined as a deviation of a measured parameter, such as FAT, energy, or V_{p-wave} , from good quality concrete. For example, a decrease in a measured FAT of greater than 30% is an anomaly (DFI, 2019). Conversely, a defect is defined as a confirmed zone of weak, missing, or segregated concrete versus just an uninvestigated deviation in a measured parameter.

Table 21. Empirical Relationship between Increase in First Arrival Time (FAT) and Percent Decrease in Compression Wave Velocity (V_{p-wave}) (DFI, 2019).

% Increase in FAT	% Decrease in V_{p-wave}
10	9
11	10
15	13
18	15
20	17
25	20
30	23
33	25
35	26
40	29
43	30
45	31

During a CSL test, the relative energy or amplitude, i.e., measure of the signal intensity of the receiver probe (DFI, 2019), of the compression wave is also recorded in the time history of the seismic signal. In general, the wave amplitude or strength increases with increasing quality of concrete. The DFI (2019) (DFI, 2019) presents a CSL rating criteria that uses reductions in relative energy along with FAT to assess CSL test results. DFI (2019) (DFI, 2019) recommends that CSL test results be classified into one of the following categories:

- **Class A:** Acceptable CSL test results
- **Class B:** Conditionally acceptable CSL test results
- **Class C:** Highly abnormal CSL test results.

The definition of each category for any section of the profile is defined by DFI (2019) as:

- **Class A:** FAT increases are less than 15% of the local average FAT and reductions in relative energy are less than 9 dB of the local average of relative energy.
- **Class B:** FAT increases are between 15 and 30% of the local average FAT and reductions in relative energy are less than 12 dB of the local average of relative energy

or

FAT increases are less than 15% of the local average FAT and reductions in relative energy are greater than 9 dB of local average.

- **Class C:** FAT increases are greater than 30% of local average FAT and reductions in relative energy are greater than 12 dB of local average.

The essential equipment and instrumentation required for CSL testing are water-filled CSL access ducts, a transmitter probe, a receiver probe, depth-measuring encoding devices, and recording apparatus. A diagram of the general testing arrangement for CSL testing is shown in Figure 40 and is reproduced from ASTM D6760. ASTM D6760 also addresses the number of access ducts that should be installed for circular deep foundations and some typical access duct configurations. In general, one access duct should be installed for every 0.75 to 1.00 ft (0.25 to 0.30 m) of drilled shaft diameter with a minimum of three (3) and a maximum of eight (8) access ducts spaced equally around the circumference (ASTM D6760). For comparison purposes, the Alabama DOT (ADOT, 2007) also provides specific guidelines for the number of access ducts based on shaft diameter as shown in Table 22.

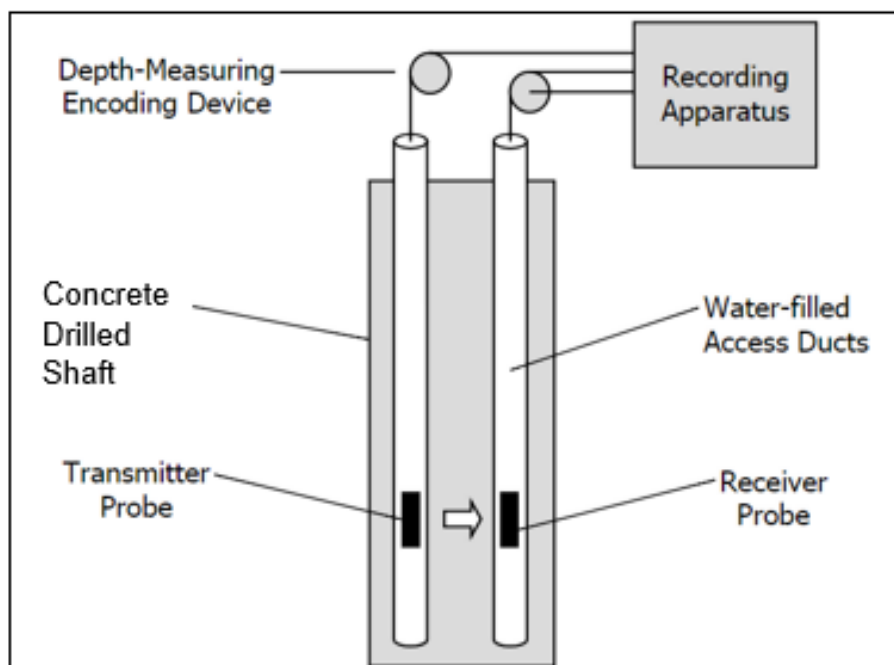


Figure 40. Illustration. Diagram of basic CSL testing arrangement (ASTM D6760).

ADOT, 2007 specifies that “CSL shall be used on all production and trial drilled shafts (a) when constructed with the placement of concrete under water or through slurry, (b) when required by special note on the plans, (c) when full length temporary casing is used to prevent water from entering the shaft, or (d) when determined to be necessary by the Engineer”. The Ohio DOT Design Manual regarding CSL and TIP testing specifies that integrity testing shall be performed for drilled shafts that meet any of the following four (4) conditions: (1) sixty (60 in.) or more in nominal diameter, (2) non-redundant foundation applications, irrespective of shaft diameter, (3) all drilled shafts constructed “in the wet” construction methods, and (4) at least ten (10) percent of all drilled shafts, or one per substructure unit, irrespective of shaft diameter (Ohio DOT, 2019).

Table 22. ADOT’s Recommended Number of CSL Access Ducts as a Function of the Shaft Diameter (ADOT, 2007)

Shaft Diameter, D	Minimum Number of Access Ducts
$D \leq 4.5 \text{ ft (1.4 m)}$	4
$4.5 \text{ ft (1.4 m)} < D \leq 5.5 \text{ ft (1.7 m)}$	5
$5.5 \text{ ft (1.7 m)} < D \leq 6.5 \text{ ft (2.0 m)}$	6
$6.5 \text{ ft (2.0 m)} < D \leq 7.5 \text{ ft (2.3 m)}$	7
$7.5 \text{ ft (2.3 m)} < D \leq 8.5 \text{ ft (2.6 m)}$	8
$8.5 \text{ ft (2.6 m)} < D \leq 9.0 \text{ ft (2.7 m)}$	9
$9.0 \text{ ft (2.7 m)} < D \leq 10.0 \text{ ft (3.0 m)}$	10
$10.0 \text{ ft (3.0 m)} < D \leq 11.0 \text{ ft (3.4 m)}$	11
$11.0 \text{ ft (3.4 m)} < D \leq 12.0 \text{ ft (3.7 m)}$	12

As part of the Deep Foundations Institute (DFI) review of CSL testing (DFI, 2019), they present some possible causes of anomalies that can occur during CSL testing. One cause is the development of bleed water, which has been observed in larger diameter drilled shafts. The bleed water can create channels along the interface between the access ducts and the concrete. These channels have been observed through subsequent coring to produce “thumb size” bleed channels that result in CSL anomalies that required shaft coring but generally not significant concern regarding the structural integrity of the shaft. SCDOT has used TIP in large part because of the high incidence of coring based on CSL report recommendations (Adams et al., 2009). Therefore, TIP was used as a companion test to CSL because it is less affected by bleed water.

To facilitate visual interpretation of arrival time measurements, the arrival time can be graphed as a function of depth as shown in Figure 41, which shows CSL results for the Control Shaft (no planned defects) in the Wisconsin DOT study conducted by Boeckmann and Loehr (2018). Each of the six (6) profiles in Figure 41 shows the first arrival time (FAT) (blue lines) and relative energy (orange lines) for each of the access duct pairings considered. In particular, from the left in Figure 41 the first four profiles are for access duct pairings with ray paths closer to the edge of the reinforcing cage, while the two profiles to the right are for the pairings with ray paths through the center of the shaft. FAT values are generally greater for the rightmost profiles because the ray path distances are greater. Even though Figure 41 shows CSL results for the Control Shaft, some anomalies in FAT and energy profiles are visible between access ducts 2-3, 3-4, and 1-4.

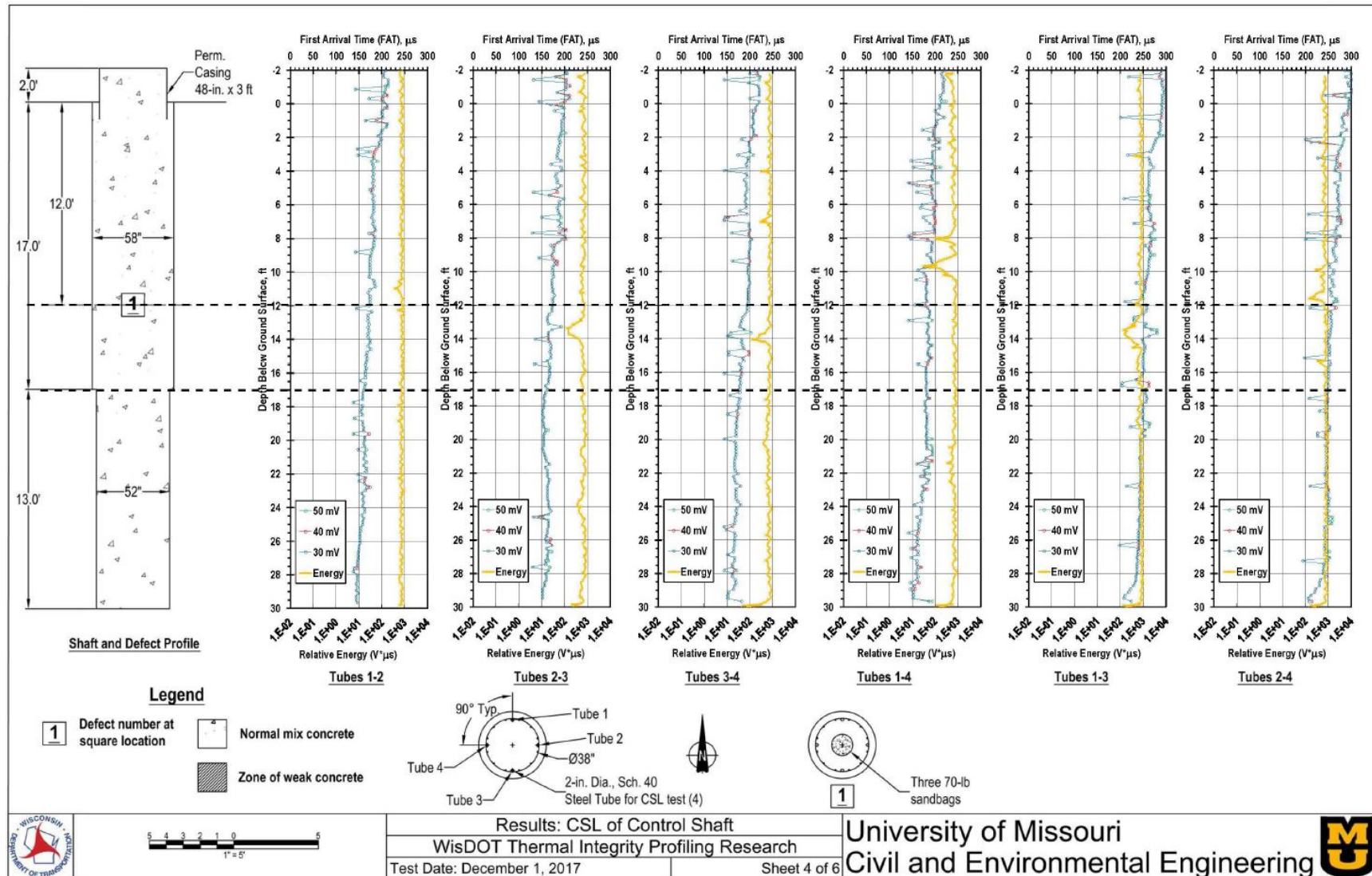


Figure 41. Graph. Graph from Boeckmann and Loehr (2018) showing arrival times (ms) and energy (dB) profiles for different access duct pairings with depth (ft) for a fifty-eight (58) inch (1.5 m) diameter test drilled shaft with a thirty (30) foot (9.2 m) tip depth with no planned defects.

The installation of CSL access tubes should be performed in general agreement with the procedure presented in ASTM D6760 or IDOT Guide Bridge Special Provision 91 available at: <http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/GBSP91.pdf>. The following summarizes installation of the CSL access tubes:

1. Obtain information related to the type of CSL access ducts to be used, the quantity of ducts per shaft, tube dimensions, and the installation method.
2. Place watertight caps on the top and bottom of each tube and water proof the couplings. With steel ducts butt welding is not permitted.
3. Attach the ducts to the inside of the reinforcing cage with tie wire to secure the pipe every three (3) ft (0.9 m). Ensure that the ducts are vertical and in parallel alignment once the cage is lifted.
4. Ensure that the ducts are installed to the bottom of the shaft base and between two (2) and three (3) ft (0.6 to 0.9 m) above the top of shaft.
5. Fill the ducts with clean water as soon as possible after the reinforcing cage is set and before concrete pouring. Never allow the ducts to be unfilled after concrete placement. This will help ensure that de-bonding does not occur and prevents ingress of debris into the access ducts.
6. Ensure the caps are attached to the access ducts until the shaft concrete has set. Do not apply excessive torque or hammering to the exposed cap during its removal to prevent de-bonding.

A potential problem with CSL testing is de-bonding between the concrete and steel access ducts at shallow depths. De-bonding leads to relatively large arrival time (and low V_{p-wave}). A zone of low V_{p-wave} at shallow depths could be interpreted as either an area of defective concrete or a zone of de-bonding. To reduce the risk of de-bonding, the access ducts should be filled with water before pouring of the concrete to prevent cooling and debonding from the access ducts. De-bonding is not considered a defect because the majority of the concrete could/should still behave as designed. Also, the access ducts should be free of debris and testing should be performed within specified time limits to prevent problems related to de-bonding as shown below in optimal time windows in Table 23.

Table 23. Optimal Time Windows to Obtain Good-Quality CSL Results (Mullins & Kranc, 2007)

Tube Type	Tube Inner Dia. (inches/mm)	Time Window
Schedule 40 Black Steel	1.5 to 2.0/38 to 50	24 hours up to 45 days
Schedule 40 PVC	1.5 to 2.0/38 to 50	24 hours up to 10 days

Another potential problem with CSL testing is bending of the access ducts during lifting of the reinforcing cage, which can compromise the threaded connections of the various pipe segments. If

the threaded connections are damaged, they must be repaired to prevent concrete from flowing into the access ducts and preventing lowering of the seismic source and/or receiver during CSL testing.

Another limitation of CSL testing stems from the CSL access ducts being attached to the inside of the vertical bars of the reinforcing cage. As a result, the test is blind with respect to the presence of shaft anomalies outside of the reinforcing cage. Consequently, CSL testing may not be the ideal integrity testing method when soil conditions are aggressive and the steel reinforcement needs sufficient concrete cover to protect the steel reinforcing from corrosion (Mullins and Kranc, 2007; Hollema and Olson, 2002).

The instrumentation typically required for CSL testing includes the following components (Olson Engineering, 2006).

1. A wheel-mounted cabling system to measure the vertical elevation of the CSL probes.
2. 35-kHz hydrophone source and receiver probes with a diameter of 1.41 inches (35.8 mm) and a length of four (4) inches (100 mm).
3. A synchronized triggering system that starts recording data at the same time the source is excited.
4. A computer system that graphically displays individual records, performs analog to digital conversion, records data and allows for data manipulation, and data output.
5. A 12-volt direct current (DC) battery source to allow for remote functionality.

The basic testing procedure is described below (Mullins and Kranc, 2007; ASTM D6760).

1. Record the top and bottom elevations to obtain the shaft length. Record the date of concrete placement and any events that merit special note during construction.
2. Sketch the shaft and assign each access tube a reference number. Record the relative distances between all of the access ducts to allow for the $V_{p\text{-wave}}$ calculation.
3. Use a tripod with the depth wheel described above set up over the test shaft and cabling should extend out from the computer to the spool to each receiver and source probes. Connect the cabling to the microprocessor and data acquisition unit.
4. CSL tests are typically performed with the source and receiver probes in the same horizontal plane. Therefore, the probes need to be lowered to the full depth and then simultaneously hand-pulled over the depth wheel at a steady rate to the top of shaft. Measurements are taken at least every 0.2 ft (61 mm) from the bottom of the drilled shaft to the top.
5. Well-trained field personnel then can evaluate whether or not the test was performed completely and accurately, however, additional analysis needs to be performed in the office to verify and delineate any observed shaft anomalies and/or defects.

CSL reports are presented in a written report that contains at least the following additional information under ASTM D6760.

1. As-built geometry of test deep foundation element including nominal or actual (or both) diameter to the nearest 0.4 inch (10 mm) and length to the nearest 4.0 inches (100 mm)
2. Test deep foundation element installation method and date, with any specific installation observations,
3. Arrangement and identification of access ducts, relative separation of ducts to the nearest 10 mm, and identifying designation documentation,
4. Profiles of the initial acoustic pulse arrival time versus depth (example shown in Figure 41) and the pulse energy/amplitude versus depth profiles.
5. Interpretation of compression wave velocity, V_{p-wave} , energy, and arrival time profiles to assess the integrity of the concrete.
6. Identification of the depth interval and tube pair that corresponds to an anomaly or defect.

If a shaft anomaly is detected, several methods may be used to isolate the location of the anomaly. If an anomaly is detected, the drilled shaft may need to be cored to verify the presence of anomalies and/or defects.

The literature review next discusses the use of Crosshole Tomographic (CT) velocity imaging of concrete defects in shafts (Paikowsky et al., 2013). The CT method is discussed and illustrated for color velocity tomograms of defects in actual bridge shafts and for constructed defects in research shafts. A final case history is presented with the results of CSL and CT of a new drilled shaft foundation for a pedestrian bridge (Paikowsky et al., 2013). The ability of CT to provide 2-D and now 3-D velocity images of a potential defect provides excellent data on the shape and severity of CSL anomalies.

Crosshole tomography (CT) is being used with CSL testing to help interpret the measured profiles and assist with determining the location and cause of an anomaly. Crosshole Tomography (CT) is an imaging method analogous to CAT-scanning in the medical industry and uses acoustic waves (Paikowsky et al., 2013). CT testing is often performed after the CSL testing has been performed to obtain more information about the size, shape, location, and severity of a suspected defect in a shaft. CT data collection is intensive and the procedure is relatively slow compared with traditional CSL testing. The spatial resolution of CT is much higher than that of typical CSL and an actual image of the shaft is produced. This method allows for the anomaly to be more precisely located and its features recorded in finer detail using three-dimensional (3D) ray paths to produce a velocity tomogram (Paikowsky et al., 2013). CT testing method is commonly used prior to coring and remediation of an anomaly.

In 2014, researchers at Florida International University (FIU) (Hajali and Abishdid, 2014) devised another variation of CSL called Frequency Tomography Analysis (FTA) which analyzes the change in frequency amplitude of the signal recorded by the receiver probe at the location of anomalies (see Figure 42). The main premise is that a 3D tomographic image aids visualization of local anomalies. Tomography is a mathematical procedure that models the shaft as a grid with each node point of the

grid assigned a property of the wave speed. The existing CSL tomographic methods are based on wave speed, which is based on the change in FAT since the distance between the CSL tubes is known. FAT of all data points in all tube combinations with known probe locations is used to solve for the wave speed at each node point. This study uses frequency tomography analysis (FTA) to convert the data to frequency at the receiver probe using Fast Fourier Transform (FFT). Using Fast Fourier Transform (FFT), the time-domain data is converted into frequency-domain data (Hajali and Abishdid, 2014). Similar to crosshole tomography, FTA attempts to determine the precise location of an anomaly and characterize its features. Each point in the drilled shaft grid is assigned a signal frequency amplitude in the FTA method to locate the anomaly (Hajali and Abishdid, 2014). In general, uniform signal frequency amplitude, i.e., small defects, produces straight ray travel paths, but variable frequency amplitude, i.e., defects, produces curved ray paths. The amplitudes of the signal in time domain and frequency domain are compared in Figure 42 to illustrate the effectiveness in identifying anomaly location.

In particular, Figure 42(a) shows the time domain results and Figure 42(b) shows the frequency tomography of CSL test data of one single path between two (2) ducts. The color contours indicate the frequency amplitude of the signal with red being the highest frequency, i.e., no defects, and blue being the lowest frequency, i.e., defects. Anomalies are represented by areas of low frequencies, i.e., slower arrival times, which is more focused in Figure 42(b). Through FTA, the anomaly is readily identified at a location of approximately 21.6 inches (0.27 m) below the top of the drilled shaft and it is located near the middle of the shaft. When compared to Figure 42(a), the time domain data does not provide the exact location and size of the anomaly (Hajali and Abishdid, 2014). In particular, Figure 42(a) shows a much larger anomaly from a depth of 16.8 inches to about 36.0 inches and much larger width of the anomaly because the blue shading extends from the center of the shaft to one edge.

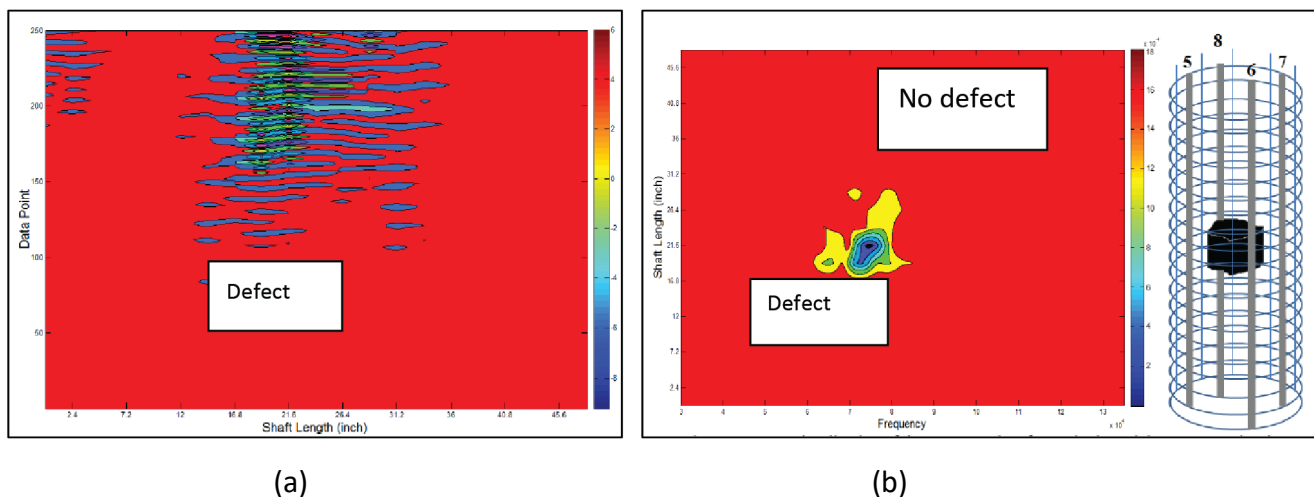


Figure 42. Graph. Shows: (a) Time Domain and (b) shows the Frequency-Domain Data from CSL testing of a drilled shaft [image from (Hajali and Abishdid, 2014)].

SONIC ECHO TESTS (SETS)

Sonic Echo Tests (also known as “Sonic Integrity Tests”) are one of the least intrusive and most cost-effective integrity tests compared with other alternatives for nondestructively testing a drilled shaft. The SET was originally developed in Holland in the 1970s to provide quality control for driven precast concrete piles. The main advantage of this test method is that the test can be performed rapidly and inexpensively and without internal intervention of the shaft (O’Neil and Reese, 1999).

This test is based on the analysis of the stress waves generated by a hammer impact that creates distortion in the drilled shaft that can be utilized to evaluate the integrity of the drilled shaft concrete. The wave types generated by the hammer impact are compression waves, shear waves, surface (Raleigh) waves, and tube (Stonely) waves, however, the V_{p-wave} is mostly used for drilled shaft quality assessments. This is similar to the low strain impact integrity testing of driven piles described in the ASTM Test Method D5882.

SETs involve measuring the elapsed time it takes for the compression wave to travel down the shaft and return to the receiver at the top of shaft. In turn, the compression wave velocity (V_{p-wave}) can be related to the hammer impact force (F). The shaft impedance (Z) is the ratio of V_{p-wave} and F. The impedance is sensitive to the cross-sectional area (A) and the concrete bulk unit weight (γ). The impedance also depends on the elastic modulus (E) and V_{p-wave} of the shaft (Webster et al., 2010). Variations in the arrival time for shafts with the same length indicate potential integrity problems.

Changes in impedance along the shaft profile cause part of the compression wave to reflect back to the surface while the remainder of the wave continues travelling to the shaft base. If an increase in unit weight or cross section is encountered, a compression wave is transmitted quicker back to the receiver at the ground surface. On the other hand, if a reduction in unit weight or cross section is encountered, a tensile wave is transmitted back to the receiver at the ground surface. Ideally, no changes in impedance are encountered and the compression wave travels back to the receiver to the maximum extent possible. In extreme cases, no return signal is received and this condition indicates a test shaft with significant anomalies and/or discontinuities.

The overall testing equipment includes an impact hammer, triggering device, vertical (z-axis) geophone, and a laptop computer with a signal conditioning unit. Accelerometers have also been used successfully, but this requires more data processing to obtain the velocity. The results of an SET show the compression wave reflection planes at the soil-concrete interface at the shaft base and the concrete-air interface at the top of shaft. The depth of the reflector is determined using the equation below:

$$Z = \frac{V_{p-wave} * \Delta t}{2}$$

where Z is the depth of the reflector, V_{p-wave} , is the compression wave velocity, and Δt is the elapsed time of the reflected compression wave. The “2” in the denominator of this equation accounts for the downward and upward motion of the compression wave. With depth to the reflector and the time required, the installed V_{p-wave} can be calculated. Using the calculated value and Table 24, the concrete quality can be determined.

Ideally, $V_{p\text{-wave}}$ should be measured using concrete samples from the same concrete batch used in the shaft construction. If testing concrete samples is not possible, the value of $V_{p\text{-wave}}$ can be estimated by reducing the values of $V_{p\text{-wave}}$ in Table 24 by five (5) percent to account for a Poisson's ratio of 0.2. To interpret an SET, the concrete quality and shaft length must be known or assumed. With these parameters, the data can be used to evaluate whether or not the reflection was from the shaft base or an anomaly (Finno and Rausche, 2010).

Table 24. Compression Wave Velocity ($V_{p\text{-wave}}$) for Excellent to Very Poor Quality Concrete (Herne et al., 1981)

Compression wave velocity ($V_{p\text{-wave}}$) ft per second/(meters per second)	Concrete Quality Based on $V_{p\text{-wave}}$
Greater than 14,200/(4,300)	Excellent
11,200 to 14,200/(3,500 to 4,300)	Good
9,500 to 11,400/(2,900 to 3,500)	Questionable
6,700 to 9,500/(2,000 to 2,900)	Poor
Below 6,700/(2,000)	Very Poor

The length to diameter ratio (L/D) also can be a critical factor in SETs. If the L/D ratio is too large, all of the wave energy dissipates into the surrounding soil. Drilled shafts in stiff clays should be limited to L/D equal to 30/1 (Herne et al., 1981) whereas shafts in silts should be limited to L/D equal to 50/1 (Hajali and Abishdid, 2014). Where the L/D ratio is too large, information from the test is only useful for the upper portion of the test shaft under the influence of the hammer impact energy.

Several types of SET have been developed in which a receiver is located either at the top of shaft or at the shaft base. The installation of a receiver at the shaft base greatly increases the cost and amount of care required during the installation of the shaft. Of course, the embedded sensors cannot be retrieved or adjusted after installation.

The main limitations to SET are: (1) information pertaining to the cross-sectional area is not provided, (2) many times only the uppermost defect can be detected because the wave is reflected back to the surface, (3) the hammer impact generates Rayleigh waves that create noise, especially to a depth of about a ten (10) ft (3.0 m) depth, (4) defects near the shaft base can be easily mistaken for defects close to the shaft top, (5) changes in impedance due to cross-sectional area or poor concrete cannot be delineated, (6) a stiff soil layer at the base or surrounding the shaft may cause reflections of the Rayleigh waves back into the shaft, (7) an increase in shaft diameter will increase shaft capacity, but such a "bulb" will appear similar to a shaft defect because of a change in response, (8) the wavelength used for SET cannot decrease much less than the shaft diameter because then multiple waves may be crossing the shaft, and (9) in stiff soils, wave attenuation into the surrounding soils can be problematic because if the base material has a similar stiffness to concrete (i.e. rock sockets) toe reflections are very weak (Finno and Prommer, 1994). In summary, SET testing is very useful to evaluate precast foundation elements, and much less so for drilled shafts, because drilled shafts almost always have variations in cross section.

IMPULSE RESPONSE TESTING (IRT)

Impulse Response Testing (IRT) is also based on compression wave ($V_{p\text{-wave}}$) measurements obtained from a SET. The difference is analysis of the SET data is performed in the time domain while analysis of the Impulse Response data is performed in the frequency domain. As a result, this testing is similar to the low strain impact integrity testing of driven piles described in the ASTM Test Method D5882.

In SET and IRT tests, the reflection of compressional waves (fastest of all wave types) from the bottom of the tested drilled shaft or from a discontinuity such as a crack, soil intrusion, or diameter change (bulb or neck) is measured (Olson Engineering, 2006). In simple terms, the generated wave from an impulse hammer travels down the drilled shaft until a change in impedance is encountered, which reflects it back to the top of the shaft where it is measured by a receiver placed next to the impact point (Olson Engineering, 2006).

IRT is better suited than SET for drilled shafts because IRT better characterizes changes in shaft diameter, whereas SET is intended for precast foundations. Still, the equipment for IRT is similar to SET, except that the impact hammer is instrumented with a load cell that measures the impact force with time. Also, a vertical (z-axis) geophone is triggered with the impact of the hammer and records the vibrations at the top of shaft. Both the hammer and geophone are connected to a laptop, which records, analyzes, and stores the test data. Unlike SET, extra care must be taken during testing to ensure the hammer strikes the shaft head squarely so that the load cell measurements are reliable (Finno and Prommer, 1994).

IRT provides test results pertaining to the shaft length, the homogeneity of drilled shaft concrete, and the value for shaft stiffness (EA). The analysis involves a Fast Fourier Transform (FFT) for the force (f) and compression wave velocity ($V_{p\text{-wave}}$) signals to convert them from the time to the frequency domain. The ratio of the velocity spectrum over the force spectrum yields the mobility spectrum (V/F in the frequency domain), which provides an indication of the velocity response of the drilled shaft to the induced excitation force (Hollema and Olson, 2002). The shaft length is obtained by evaluating the change in frequency between resonant peaks (Finno and Prommer, 1994). If the calculated shaft length is less than the expected value, an anomaly exists in the shaft profile.

The linear portion of the mobility curve is used to obtain the dynamic stiffness of the drilled shaft, which helps determine whether or not the drilled shaft contains a bulge or necking. The dynamic stiffness is calculated with the following equation:

$$E' = \frac{2\pi * f_m}{\left[\frac{V_0}{F_0} \right]_m}$$

where E' is the Dynamic Stiffness, f_m is the frequency, and the ratio $(V_0/F_0)_m$ is the Mobility. Drilled shafts founded in loose soil and shafts with soil inclusions, necks, and breaks will have lower stiffness values compared with sound shafts founded in solid soils (Finno and Prommer, 1994). Also, it is worth noting that it is easier to determine if a bulb or neck has occurred with IRT compared with SET, which makes this testing method better for drilled shafts. The limitations of IRT include: (1) as a surface

reflection method, results depend on measuring reflected responses, (2) there is a limiting L/D ratio based on soil conditions, (3) this method is subject to the problems associated with propagation of surface waves, (4) there is a limit on the size of defect that can be detected, i.e., very small defects are not detected whereas the larger the defect the greater the potential to reflect the compression wave back to the top of the drilled shaft, (5) if multiple defects exist only the uppermost defect is discernable, and (6) to interpret results, the concrete compression wave velocity (V_c) or the shaft length (L) must be known or estimated using Table 24.

GAMMA-GAMMA LOGGING (GGL)

Gamma-Gamma Logging (GGL) is a radiographic technique that utilizes a source of ionizing radiation that is lowered down an access tube similar to a CSL access tube. The probe emits the radiation and contains a gamma-ray detector as shown in Figure 43. The basic theory states that the number gamma-ray photons per unit of time that are reflected from the nuclei of the modules of the material surrounding the tube and return at a given energy level to the detector is related to the density of material surrounding the tube. In general, the lower the scatter count, the denser the material (CALTRANS, 2015). An advantage of GGL is that it does allow an assessment of the concrete outside of the reinforcing cage and the zone between the reinforcing cage and borehole wall (O'Neil and Reese, 1999). However, GGL is commonly used only in California (O'Neil and Reese, 1999).

The main benefit of GGL is it evaluates the homogeneity of the concrete. Local changes in density can be detected in the cover zones, constituting an advantage over CSL testing, which does not provide information of the cover zones. In general, however, GGL only provides information on the density of concrete within a four (4) inch (100 mm) radius from the access tube (O'Neil and Reese, 1999).

The installation of access ducts for GGL testing should satisfy the following requirements: (1) one access tube should be used per foot or meter of shaft diameter (ASTM D6760), (2) access ducts should be placed at least three (3) inches (76 mm) away from any vertical reinforcement and spaced equally, (3) due to the length of the gamma-gamma probe, vertical alignment of the access ducts must be maintained such that a two (2) foot (0.6 m) long by 1.9 inch (48 mm) diameter rigid cylinder can pass from the top to the bottom of the tube, (4) the access ducts must be kept in straight alignment and parallel to the steel reinforcement, and (5) special training and licensing is required to handle and transport the device due to regulations of the Nuclear Regulatory Commission.

The standard GGL probe has a 1.87 inch (47 mm) diameter and emits radiation from a 10 millicurie Cs 137 source. Importantly, abandoning a lodged device and grouting it in place is not an option. In one well-documented case, two (2) weeks were required to retrieve the device from the access tube (Adams et al., 2009). The testing method is also time-consuming compared with other testing methods. Typical testing consists of continuous counts taken as the test probe is raised from the shaft base at ten (10) to twelve (12) ft per minute (3.0 to 3.7 m/minute). The procedure takes about two (2) hours to log all of the inspection pipes for a four (4) foot (1.2 m) diameter pile with a one-hundred (100) foot (30.5 m) length (CALTRANS, 2015).

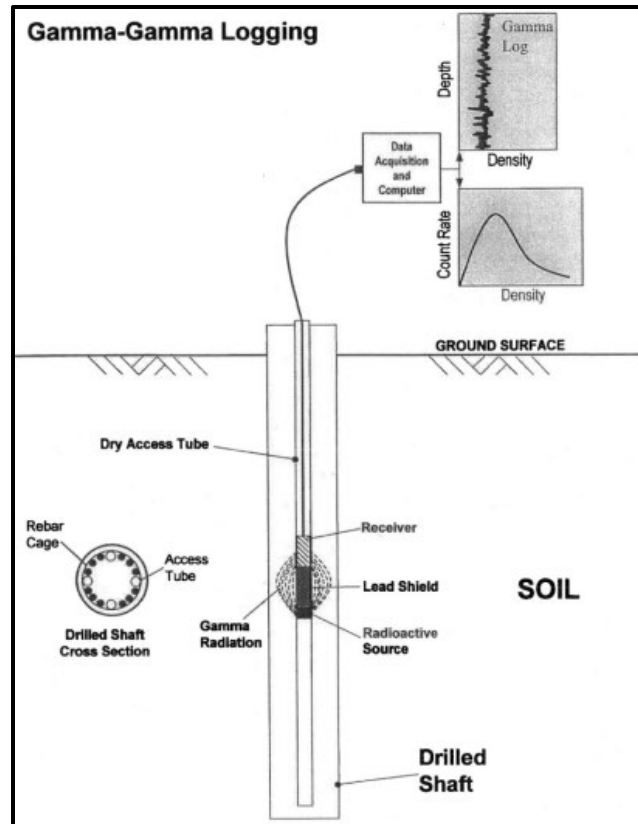


Figure 43. Illustration. Test schematic for a Gamma-Gamma Logging Test (Davis & Hertlien, 1993).

GGL test data is processed by graphing the bulk density versus time. Next, the data from different shafts using the same probe is compared and the redundant and insignificant data is discarded. Specifically, the mean, mean minus two standard deviations, and the mean minus three standard deviations are plotted on the same graph. The interpretation of the test results requires experience, engineering judgement, and statistical analysis. Generally speaking, when the bulk density or unit weight of concrete is less than the mean minus three standard deviations, an anomaly is assumed to be present in the drilled shaft (O'Neil and Reese, 1999).

In San Diego, California, results from GGL testing as well as the Miniature Shaft Inspection Device (*Mini-SID*) testing (Sinnreich et al., 2019) were used for a small trestle bridge. The Mini-SID indicated some sediment remained on the shaft bottom (Sinnreich et al., 2019). The rebar cage for this drilled shaft was equipped with nine 2 inch diameter PVC access pipes for GGL testing (Sinnreich et al., 2019). The GGL testing also indicated several zones of decreased concrete bulk density with the largest near the bottom, which indicated remedial measures may be needed (Sinnreich et al., 2019). To obtain additional information, the nine access tubes were used for CSL testing and this testing indicated only minor anomalies after aligning the data to the correct elevations that did not warrant remediation. The shaft was then load tested using the bi-directional test method with an Osterberg Load Cell and it did not show a "soft toe" in the load-displacement relationship. Based on the CSL testing and load test, the shaft was accepted without remediation so using multiple testing is recommended for drilled shaft acceptance (Sinnreich et al., 2019).

The results of this San Diego project reinforced anecdotal evidence in California that GGL data related to end bearing in wet shafts was unreliable due to poor results near the shaft base (Sinnreich et al., 2019; Broeckmann, 2015). In particular, the results from GGL testing can indicate poor quality concrete at the shaft base so load transfer into end bearing is questioned and a reduced value has to be used for design purposes (Sinnreich et al., 2019). However, load tests performed on shafts with poor GGL results at the toe of the shaft, e.g., the shaft in San Diego, did not indicate a soft toe (Sinnreich et al., 2019). Other nondestructive tests, e.g., CSL and TIP, also have indicated shaft integrity issues but the accompanying load tests yielded problems in only about five of these shafts out of hundreds load tested (Sinnreich et al., 2019). This discrepancy could be caused by misinterpretation of the nondestructive test results and the benefits of load testing (Sinnreich et al., 2019).

GGL testing was also performed for the Crockett Viaduct and Interchange, Richmond-San Rafael Bridge, and Carquinez Bridge and the results were not conflicting regarding shaft end bearing (Liebich, 2004). The Crockett Viaduct utilized GGL on five (5) drilled shafts involved in a load test. The load consisted of a test shaft and four reaction shafts (Liebich, 2004). Three of the reaction shafts showed a total of four anomalies via FFT (Liebich, 2004). Subsequent CSL testing indicated uniform concrete within these reaction shafts at 3 of the 4 GGL anomaly locations (Liebich, 2004). Regardless, the test shaft was load tested without any issues (Liebich, 2004). Afterwards, the top 30 ft (10 m) of the three reaction shafts were excavated and the anomalies at the GGL location were visually confirmed (Liebich, 2004). In addition, where the CSL testing indicated an anomaly coincident with the GGL, the anomaly extended in to the shaft so it was detected by the CSL testing (Liebich, 2004). Where the CSL indicated no anomaly but the GGL did, the anomaly was confined primarily to the shaft perimeter and only extended to the reinforcing cage. No undetected defects were observed during the 30 ft excavation (Liebich, 2004).

The Richmond-San Rafael Bridge also utilized GGL and CSL testing on 5.9 to 13.2 ft (1.8 and 4 m) diameter drilled shafts (Liebich, 2004). One of the 13.2 diameter drilled shafts at Pier 38 was constructed to a tip elevation of (-58.8 m) using polymer slurry and tremied concrete. GGL detected anomalies in 7 of the 12 inspection tubes located on the interior of the reinforcing steel cage in the bottom 6.6 ft (2 m) of the shaft while the remainder of the shaft was homogeneous and of good quality (Liebich, 2004). Afterwards, CSL testing was performed via 12 steel inspection tubes, which showed the anomaly was outside the steel cage indicated a “bullet-shaped” tip. The contractor used water-jetting in the GGL PVC inspection tubes to clean out the anomalies and then grouted the tip area. Based on this repair, the drilled shaft was accepted and it showed the complementary nature of GGL and CSL testing.

The Carquinez Bridge project utilized 9.9 ft (3.0 m) in diameter and 302.6 ft (92 m) long drilled shafts with 154.6 ft (47 m) in Bay mud and 148.0 ft (45 m) of rock socket (Liebich, 2004). GGL was conducted on a problematic drilled shaft and the tremie break that occurred during shaft construction was identifiable as well as several other anomalies in this shaft. CSL testing was subsequently conducted on the shaft, which verified weak soil across the shaft section (Liebich, 2004). The contractor drilled a 1.6 m diameter hole in the shaft to a depth of 10 m to access and remediate the defect at the tremie

break (Liebich, 2004). This defect was large enough that GGL was sufficient to identify and size the anomaly but the CSL testing provided good confirmation.

The main advantages of GGL is that the method is: (1) not restricted by shaft length, (2) multiple defect types can be detected, (3) concrete density can be determined in a limited extent of the drilled shaft, (4) concrete quality in the cover zones can be determined. The major limitations are that (1) pre-installed access ducts are required, (2) the test is relatively expensive, (3) the shaft cross section is not evaluated, and (4) as mentioned previously, radioactive materials are used (O'Neil and Reese, 1999).

CONCRETEOSCOPY (CT)

Concreteoscopy is an optical inspection method that involves one-half (1/2) inch diameter clear plastic tubes attached to the reinforcing cage at intervals around the cage. A miniature camera attached to a fiber-optic cable is used to view concrete in real time through the clear plastic tubes. This viewing can occur during concrete placement so the concrete can be stopped and remedied if a problematic situation develops. This viewing is analogous to a physician viewing the interior parts of the human body (O'Neil and Reese, 1999). After concrete placement, only the concrete in direct contact with the tubes can be evaluated, and only a visual confirmation of the concrete integrity is furnished around the tubes (O'Neil and Reese, 1999). The video can be made of the viewing and played at the office or in the field. Photographs can be obtained from the video to distribute to different entities.

CT testing is similar in operation to the gamma-gamma test except that visual interpretation is used instead of density monitoring to evaluate the quality of the concrete (O'Neil and Reese, 1999). The main disadvantage of CT testing is the quality of concrete between the tubes is not assessed however, cracking and honeycombing of the concrete can be detected (O'Neil and Reese, 1999). Because of this limitation, CT testing is effective when used in combination with another nondestructive test method, such as CSL or gamma-gamma testing (O'Neil and Reese, 1999). Another disadvantage is that expensive photographic and recording equipment is required (O'Neil and Reese, 1999). CT testing or inspection is not widely used, so reliable cost information was not available from local consultants.

PARALLEL SEISMIC IMPULSE TESTING (PSIT)

Parallel Seismic Impulse Testing (PSIT) is an integrity test that was first developed during the 1970s in France to evaluate the integrity of deep foundations that were part of existing structures to assess the length of pre-existing foundations. PSIT is another direct transmission integrity testing method (Hollema and Olson, 2002). However, because large voids or bulges can be identified along the deep foundation edge, it is not typically used for identifying defects. The basic procedure involves drilling a borehole next to an existing deep foundation, extending somewhat deeper than the deep foundation and within three (3) ft (0.9 m) of the deep foundation.

Alternatively, the hydrophone assembly can be lowered into a cored borehole inside of the foundation itself, a procedure known as the "downhole seismic method." In the downhole seismic

method, tube (or Stonely) waves are generated in addition to compression waves, with an approximate wave speed equal to five thousand (5,000) ft per second (1,525 m/second) and having a larger amplitude than compression waves ($V_{p\text{-wave}}$). However, for practical purposes related to integrity testing of deep foundations, the $V_{p\text{-wave}}$ is the more important wave form (Liebich, 2004).

In either case, an impact hammer causes stress waves to propagate down the length of the foundation. The boreholes drilled within 2 to 3 ft (0.6 to 0.9 m) of the existing deep foundation must be water-filled so that the $V_{p\text{-wave}}$ can be detected with a hydrophone. The depth increment is typically every twenty (20) inches (50 cm). In this manner, a profile of signals is obtained along the length of the deep foundation. Hammer impact energy can reach the hydrophone to depths up to 130 ft (40 meters) in ideal conditions. The hydrophone can typically withstand a hydrostatic water pressure of 43 psi (296 kPa) that corresponds to the dynamic water pressure increment generated by the hammer impact (Liebich, 2004).

PSIT testing requires an impact hammer, hydrophone device, and a data acquisition system with a triggering mechanism that is excited by energy from the impact hammer. PSIT results for a shaft free of discontinuities should yield an arrival time that proportionally increases with depth. The shaft base can be detected because the change in stiffness between the shaft itself and the shaft base material has the effect of increasing the compression wave arrival time (Liebich, 2004).

The most useful information that is obtained from PSIT and downhole seismic testing is the compression wave velocity ($V_{p\text{-wave}}$) profile, which is sensitive to discontinuities in the deep foundation. These discontinuities are caused by variable quality of concrete, cracks and joints that form during concrete curing, soil inclusions, and the change in stiffness between the shaft and its base. Since all of these conditions lead to non-linear P-wave profile, it is difficult if not impossible to verify which type of condition exists in a given test shaft (Liebich, 2004).

THERMAL INTEGRITY PROFILING (TIP)

Thermal Integrity Profiling (TIP) is a recent development for integrity testing of drilled shafts pioneered by Gray Mullins at the University of South Florida (Webster et al., 2010). TIP testing measures and utilizes the temperature time history of the drilled shaft concrete associated with the heat of hydration. The TIP test method has undergone several iterations and improvements since its development by the University of South Florida in late 1980s. In general, TIP is advantageous because it provides information related to the integrity of the re-bar cage cover zones (Webster et al., 2010), shaft radius, and the interior of the drilled shaft.

Initially, the thermal probe and test were designed as an add-on to cone-penetrometers. It was conceived that soil temperature variations adjacent to deep foundations could be measured by equipping a cone penetrometer with thermo-couples. Discontinuities and other problematic drilled shaft issues were to be identified by variations in the soil temperature along the length of the drilled shaft. However, due to the limited soil types suited for cone penetrometer testing, i.e., soft to medium fine-grained soils and loose to medium coarse-grained soils, the applications for this particular version of the TIP device were quite limited.

Once access ducts were installed regularly in drilled shafts for CSL testing, the TIP concept was reconfigured to capture temperature signatures from the interior of drilled shafts using thermal probes rather than through the soil temperature. This required deploying a thermal probe in each of the CSL tubes throughout the concrete hydration process. Although this method provided superior performance compared with previous versions, it was not until the next iteration of the test that TIP testing gained adoption for drilled shaft nondestructive testing. The latest iteration of the TIP test removes the need for access ducts and instead uses sacrificial thermal wires that are attached directly to the reinforcing cage and permanently embedded in the concrete (Method B). Each thermal wire has thermo-couples spaced at one (1) foot (0.3 m) increments with at least one wire per foot (0.3 m) of shaft diameter. The thermal wires are then attached to a portable data acquisition system so that the temperature time history of the curing concrete is measured along the shaft length with time. A few days (usually less than three (3) days) after the drilled shaft is constructed, the portable data acquisition system is retrieved from the field. Also, if this so-called “Method B” is used, access ducts are not needed to perform the test and do not have to be attached to the reinforcing cage unless CSL testing will also be performed. IDOT requires Method B, i.e., embedded sensors, to be used for TIP testing.

The installation of thermal sensors should be performed in general agreement with the procedure presented in ASTM D7949 or IDOT Guide Bridge Special Provision 92 available at: <http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/GBSP92.pdf> (IDOT, 2019) and summarized below.

Table 25 shows the number of access locations for embedded thermal sensors as a function of the reinforcing cage diameter (Davis and Robertson, 1976).

Table 25. Number of Access Locations for Embedded Thermal Wires as Function of the Reinforcing Cage Diameter (Davis & Robertson, 1976)

Reinforcing Cage Diameter (ft/m)	Number of Access Locations for Embedded Thermal Sensors
Less than or equal to 5.0/1.5	4
5.1 to 7.0/1.5 to 2.14	6
7.1 to 9.0/2.17 to 2.74	8
9.1 to 11.0/2.78 to 3.36	10
11.1 to 13.0/3.39 to 4.00	12
Greater than 13.0/4.00	14

If a drilled shaft has continuous concrete of consistent quality and sufficient concrete cover over the reinforcing cage, the temperature profile will be constant with depth. Shaft anomalies that may or may not be defects can be identified by variations in the temperature profile. The most prominent phenomenon causing anomalies, the anomaly types, and the source of each anomaly are shown below in Table 26 from Mullins and Kranc (2007). In general, there are three (3) categories of anomaly type, (1) boundary condition changes around the drilled shaft exterior of the shaft, (2) heat

source changes inside the shaft, and (3) diffusivity gradient (D), which could be caused by the reinforcing steel (Mullins and Kranc, 2007). Diffusivity involves the concrete heat diffusing to lower temperature areas or items, such as steel. D is a scalar product that is calculated using the following equation: (Mullins and Kranc, 2007).

$$D = \text{Temperature Gradient} * \text{Diffusivity Gradient}$$

Figure 44 illustrates the basic arrangement of the TIP testing equipment and arrangement. The thermal wires attached to the vertical bars of the reinforcing cage before the insertion of the reinforcing cage in the shaft excavation.

Based on the uniformity or non-uniformity of the peak temperatures during the concrete hydration process, the presence of shaft anomalies can be identified. The measured temperature profile is sensitive to changes in cross section, reinforcing cage alignment, soil contamination, and decrease in concrete cover because these factors change the amount of concrete and thus the magnitude of temperature during concrete hydration (Mullins and Kranc, 2007).

Table 26. Most Common Thermal Anomaly Types and Their Descriptions (Mullins and Kranc, 2007)

Phenomena	Anomaly Type	Anomaly Source
Groundwater Surface	Boundary condition	Higher specific heat of water than concrete so heat is removed from the completed drilled shaft
Aggregate	Heat source (none)	Lack of heat production within the shaft by aggregates
Reinforcing bar	Diffusivity gradient (large change in temperature in small area)	Very high heat conductivity or absorption by re-bar cage
Shaft toe	Boundary condition	Vertical heat flow condition from the shaft into the underlying geologic material(s)
Tremie pipe raise	Heat source variability	Differences in concrete mix age and/or proportions produce different levels of temperature with older concrete heating and cooling first
Soil Slump	Heat source & Boundary condition	Lack of heat production & reduction in heat within the shaft

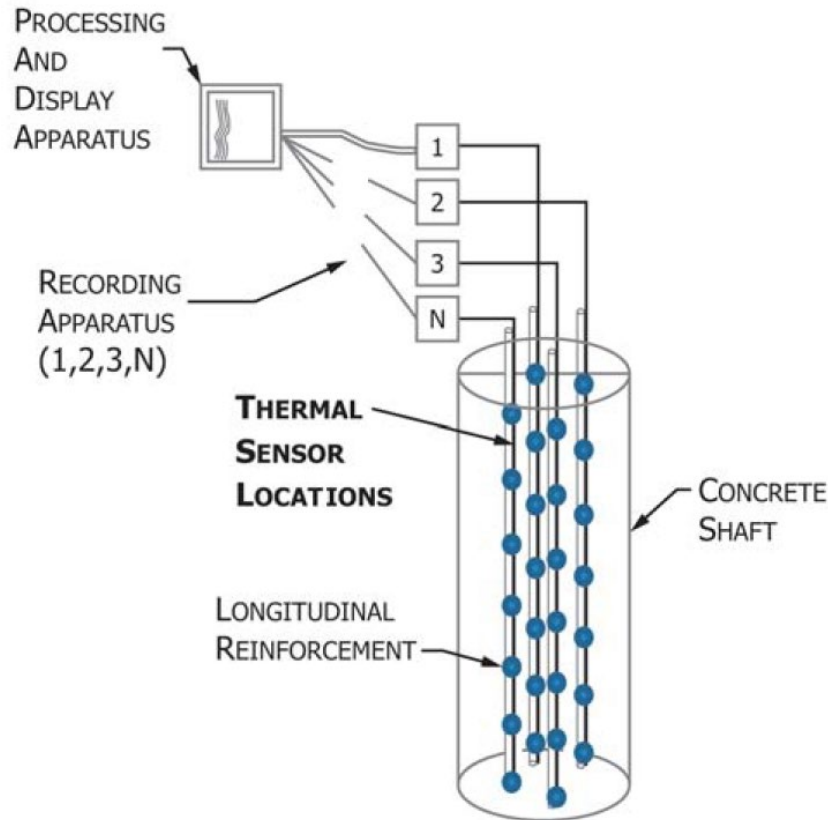


Figure 44. Illustration. Schematic diagram of the TIP testing (Method B) arrangement, including thermal wires, thermal access ports (TAPS), computer, and remote data transmitter (ASTM D7949).

Figure 45 shows the distribution temperature due to concrete hydration in an idealized drilled shaft and the dissipation of heat to its surroundings across the drilled shaft. For an idealized cylindrical drilled shaft, the temperature is highest at the center of the shaft and decreases to the edges. This radial temperature distribution is bell-shaped as shown in Figure 45. In addition, the vertical distribution of temperature decreases at the top and bottom of the drilled shaft due to heat dissipation into the atmosphere and geologic materials at the top and bottom of the drilled shaft, respectively. The decrease in temperature at the top and bottom of the shaft is referred to as the temperature “roll-off”. As shown in Figure 45, the data collected in accordance with ASTM D7949 yields a continuous temperature profile vertically and discrete measurements laterally (indicated by red dots) (Johnson, 2016). The vertical profile is used to identify any bulges, necks, or inclusions in the drilled shaft that may be present, while comparison among tube temperatures indicates lateral cage alignment (Johnson, 2016).

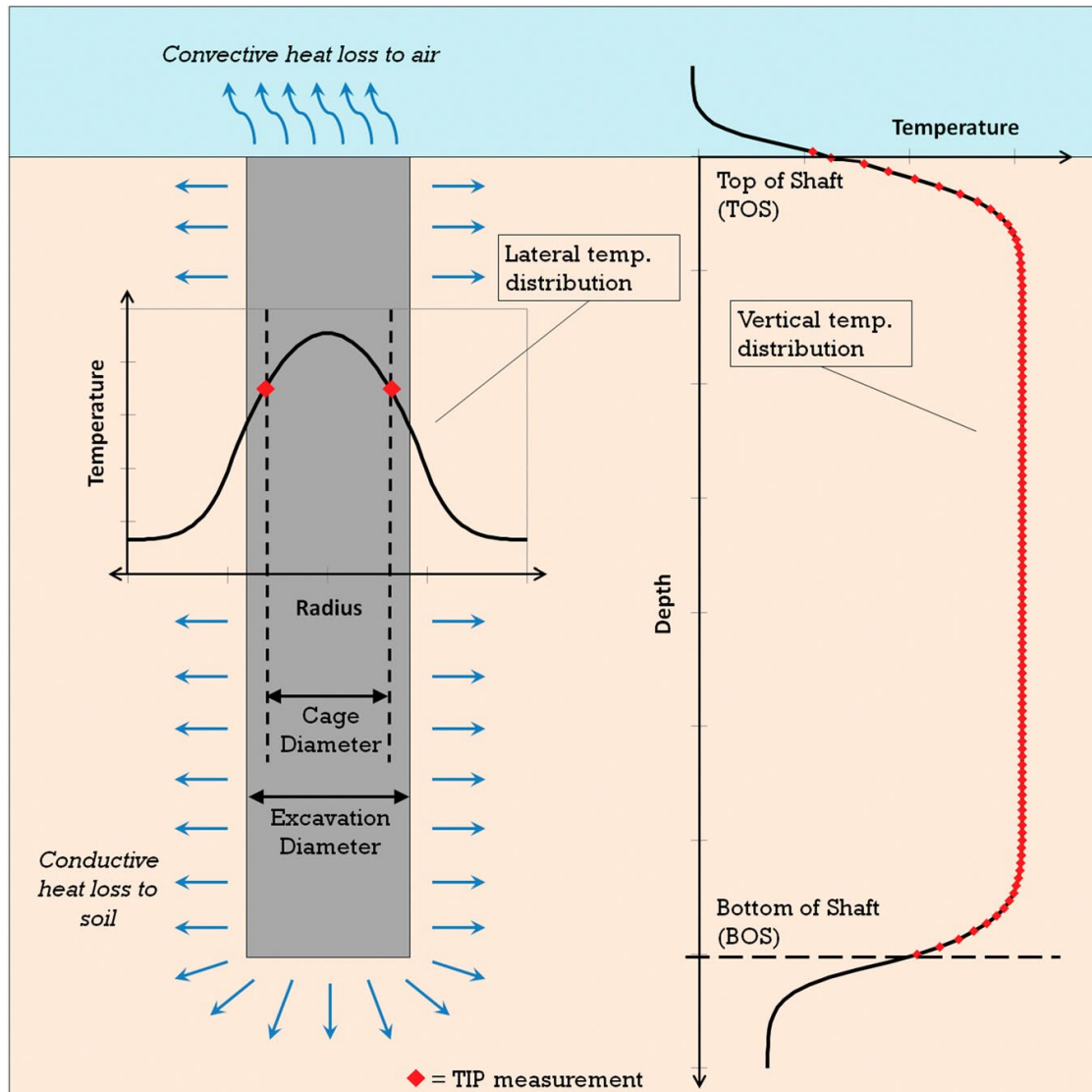


Figure 45. Illustration. Temperature distribution and dissipation due to concrete hydration in idealized shaft (image from Johnson, 2016) (ASTM D6760).

Observation of the measured temperature profiles provides qualitative information about shaft integrity, such as general shape, relative cage alignment, and the types of anomalies that may be present (Johnson, 2016). For example, if the temperature profile is relatively consistent, as shown in Figure 45, the cross-sectional properties and integrity of the drilled shaft concrete are consistent and considered adequate. Conversely, if there is an increase or decrease in temperatures in various or all thermal wires this indicates a bulge or neck in the shaft, respectively, whereas an equal but opposite variation of opposing tube temperatures indicates cage eccentricity (Johnson, 2016). Circular shaped temperature roll-offs that extend about one diameter from the top and bottom of the shaft indicate normal end conditions (Johnson, 2016).

Figure 46 presents temperature profiles for two different drilled shafts to illustrate typical behavior and some defects. Figure 46(a) illustrate typical shaft top and bottom temperature conditions, which

involve a reduction of temperature. At the bottom of the shaft (BOS) the temperature decreases due to the presence of soil or rock at a lower temperature than the curing concrete. At the top of the shaft (TOS) the temperature also decreases because the ambient temperature is lower than the curing concrete. However, at the TOS the temperature may increase due to sunlight warming the top of the shaft but this is limited in depth. Figure 46(a) also shows the presence of a bulge, or increased diameter, of the shaft between a depth of 35 and 40 ft, which could be due to soil caving. Figure 46(b) also shows an offset of the reinforcing cage at a depth of 15 to 30 ft because the temperature in Tubes 1 and 4 are significantly less than Tubes 2 and 3. There is also a significant difference in temperatures in Tubes 1 and 3 at a depth of 60 to 70 ft, which also may be caused some offset of the reinforcing cage.

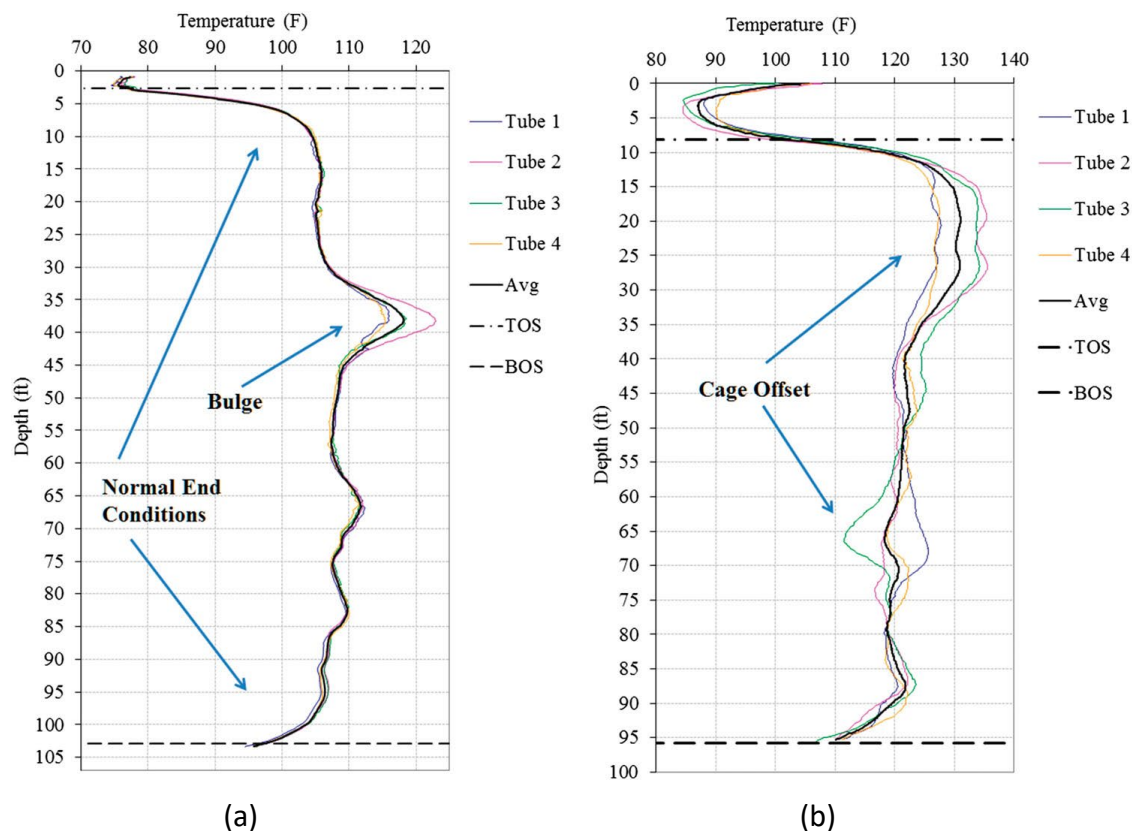


Figure 46. Graph. Temperature distribution and dissipation due to concrete hydration in two non-idealized drilled shafts (images from Johnson, 2016) (Johnson, 2016).

Differential temperatures can also be used to estimate the thickness of concrete covering the reinforcing cage and radius of the drilled shaft. Figure 47(a) illustrates the differential temperature profiles that can be used to estimate reinforcing cover thickness and an anomaly or defect in the completed shaft (Piscsalko et al., 2016). The data in Figure 47(a) corresponds to a 10 ft (3.0 m) diameter shaft that is 125 ft (38.1 m) long. The ten (10) temperature profiles in Figure 47(a) were measured over 120 hours after completion of the drilled shaft. The temperature profiles indicate a large temperature reduction at about 90 ft (27.5 m) below the top of the shaft (Piscsalko et al., 2016). Using the estimated volume of the drilled shaft based on its initial dimensions, the temperature

profiles can be converted into an effective shaft radius and concrete cover profile as shown in Figure 47(b) (Piscsalko et al., 2016). In particular, Figure 47(b) shows the concrete cover on one side of the shaft (thermal wire locations 6 through 10) at a depth of 90 ft (27.5 m) was less than the minimum allowable concrete cover (6 inches/0.15 m). This reduced concrete cover corresponds to a total reduction in radius at 90 ft (27.5 m) of 14.2% and thus this shaft should be classified as an anomaly under either the radius reduction or minimum concrete cover criteria discussed below and warrants further evaluation in that zone (Piscsalko et al., 2016).

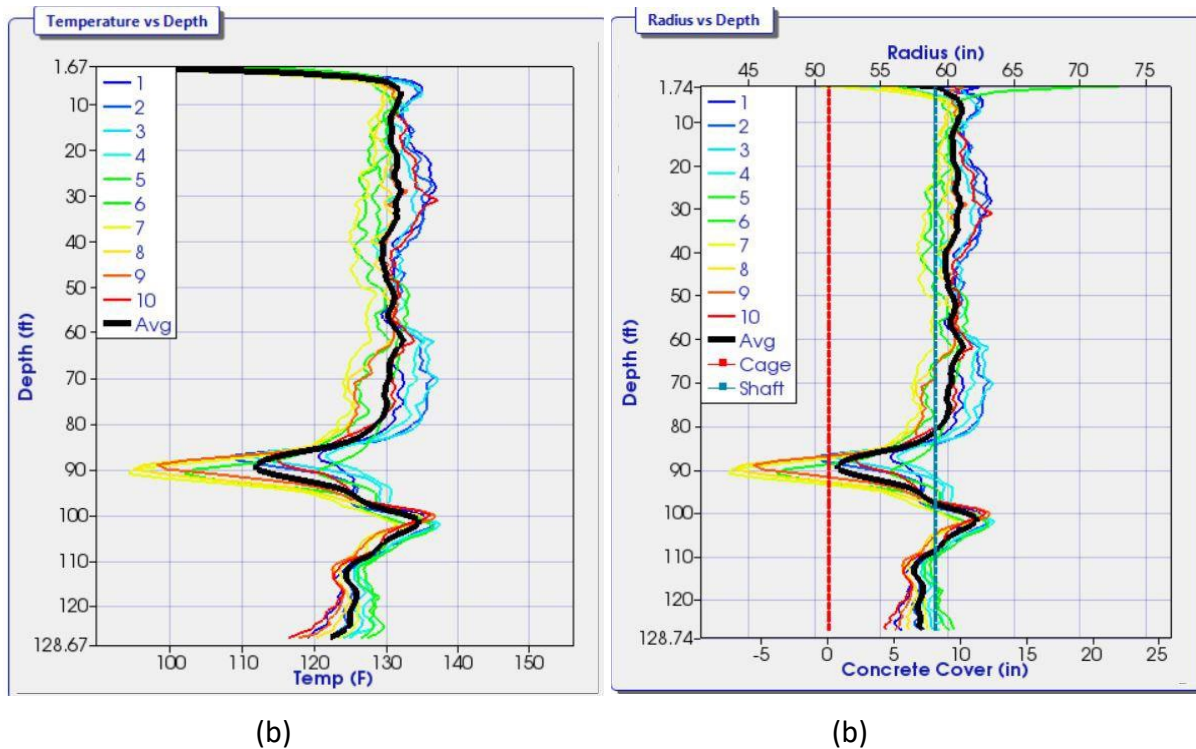


Figure 47. Graph. Shows: (a) ten different temperature profiles with an average profile (black line) and (b) shows the estimated shaft radius and concrete cover based on the measured temperature profiles (images from Piscsalko et al., 2016 (Piscsalko et al., 2016)).

In addition, thermal wire locations 6 through 10 at a depth of 90 ft (27.5 m) indicate that the defect extended inside the reinforcing cage (Piscsalko et al., 2016). The percent radius reduction of 14.2% corresponds to a reduction of 26.3% in drilled shaft cross-sectional area, which also triggered structural and geotechnical concerns along with the concrete cover durability issue as discussed below (Piscsalko et al., 2016). Further evaluation included coring of the shaft which confirmed the defect at this location, which was a lack of cement and only aggregate being present at a depth of 90 ft (27.5 m) below the top of the shaft (Piscsalko et al., 2016). The coring location was approximately 6 inches (0.15 m) inside the reinforcing cage and located between thermal wires 7 and 8, which was the location that the TIP testing revealed as having the greatest loss in effective radius (Piscsalko et al., 2016). This defect was repaired using pressure grouting, saving the project from a potentially costly foundation failure (Piscsalko et al., 2016).

While the average shaft 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 recommends minimum cover of 4 inches (100 mm) is often used but individual states have adopted different acceptance criteria based on local needs or conditions. 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 27 for shafts with a diameter of 3 to 9 ft. The radius reduction is calculated by dividing the as constructed radius by the design radius. Based on the shaft impacts in Table 27, the acceptance criteria used above was developed and is summarized below for shafts with a diameter of 3 to 9 ft (Piscalko et al., 2016):

- Satisfactory Drilled Shaft Construction

0 to 6% Radius Reduction and Local Concrete Cover Criteria Achieved, e.g., 4 inch (100 mm) cover for 6 ft (1.8 m) diameter shaft

- Anomaly Requiring further evaluation

Radius Reduction > 6% or Local Concrete Cover Criteria Not Achieved, e.g., 4 inch (100 mm) cover for 6 ft (1.8 m) diameter shaft

When a tested shaft is categorized as having an anomaly, 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 (Johnson, 2016). 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 vetted along with the TIP results to determine acceptance of the shaft (Mullins and Winters, 2011).

Table 27. Effect of Radius Reduction, As-Built/Design Radius, on Four Drilled Shaft Performance Indicators (Johnson, 2016)

% Radius Reduction	% Loss in Bending Capacity	% Loss in Axial Compression Capacity	% Loss in Side Resistance	Loss in Concrete Cover Thickness (4 in. (100 mm) cover for 6 ft (1.8 m) diameter shaft)
3%	11%	6%	3%	1.08 in/27.4 mm
6%	22%	12%	6%	2.16 in/54.9 mm
>6%	>22%	>12%	>6%	>2.16 in/54.9 mm

TIP can be analyzed at various levels ranging from direct observations to detailed signal matching field measurements with numerical models. Depending on the results of the profiles a more or less intense analysis may be needed. In some instances, especially when multiple shafts are tested on a site, direct evaluation of the temperature profiles for temperature magnitude and basic profile shape is all that is needed. These analyses have been broken into the following four levels of review:

- Level 1: Direct observation of the temperature profiles
- Level 2: Superimposed construction logs and concrete yield data
- Level 3: Three-dimensional (3D) thermal modeling
- Level 4: Signal matching numerical models to field data

In most cases, a Level 2 analysis is all that is necessary. However, more detailed Levels 3 and 4 analyses can be employed when highly unusual thermal integrity profiles arise (Mullins and Winters, 2011).

Level 1 analysis identifies the top and bottom of shaft based on normal/anticipated profile roll-off shapes. This information can be used to verify the overall shaft length, confirm proper cage alignment, locate changes in shaft diameter and identify immediate areas of concern. There is no need for further evaluation if the top and bottom of shaft (and length) are clearly seen and the top and bottom “roll-off” zone appears normal (approximately 1 to 2 diameters deep for 4 ft (1.2 m) diameter shafts) (Mullins and Winters, 2011). The “roll-off” zone or depth at the top of the shaft increases with shaft diameter and can be estimated using 1 to 2 times the shaft diameter.

To better evaluate the results and define the significance of various thermal profile features, a Level 2 analysis can be performed that makes use of additional site and construction information to confirm the direct observations made in Level 1. The concrete yield information can also be used to define a temperature–radius correlation that defines the shape of the as-built shaft. The extent of cage eccentricity is further defined in a Level 2 analysis because it is recognized but not quantified in Level 1 (Mullins and Winters, 2011).

Levels 3 and 4 analyses require the use of a thermal modeling software like TIP View, which utilizes Visual Basic for Applications (VBA) programming for analyzing thermal data. The main shortcoming of TIP testing is temperature “roll-off” due to heat loss at the base of the excavation and near the ground surface (Brown et al., 2010; Davis and Robertson, 1976). In the data set above in Figure 46, the affected regions are less than about ten (10) vertical ft (3.0 m) from the shaft base and ground surface.

In 2011, the Washington DOT (WSDOT) conducted a research project by Mullins and Winters (Mullins and Winters, 2011) to develop thermal integrity testing procedures. Out of the eight (8) WSDOT projects in which TIP testing was performed, none of them required an analysis beyond Level 2. The eight projects involved drilled shafts with diameters of 4, 6.5, 7, 8, 9, 10, and 12 ft and various geologic conditions.

Unlike the WSDOT, the 2018 research project conducted by the Wisconsin DOT focused on one (1) research site to test the ability of TIP and CSL to detect simulated defects (Boeckmann and Loehr, 2018). To evaluate the ability to detect defects with TIP methods compared with CSL methods, Wisconsin DOT constructed three four (4) ft diameter shafts each 30 ft long with ten (10) intentional defects in Waukesha, Wisconsin. The defects varied in location, size, and material. TIP and CSL tests

were performed on all three shafts. The results revealed TIP and CSL to be complementary. Table 28 summarizes the intentional defects included in these three (3) test shafts.

Table 28. Summary of Wisconsin DOT Intentional Defects (Boeckmann and Loehr, 2018)

Shaft Defect	Modeled Defect	Test Shaft	Depth of Defect	Defect Location in Shaft	% of Defect Size to Shaft Area
1	3 sand bags in cage interior	Control	15 ft	Center of shaft	10%
2	Soft bottom: 6 sand bags at cage bottom	Test Shaft #1	30 ft	Entire shaft diameter	50%
3	Necking: six sand bags around outer edge of cage	Test Shaft #1	15 ft	Center of shaft	10%
4	Debonded CSL tubes-grease applied to CSL Tube	Test Shaft #1	16.5 ft	Reinforcing cage	N/A
5	Defect outside cage – 2 sand bags one side of cage	Test Shaft #1	12 ft	1/3 cage perimeter	10%
6	Weak concrete mix	Test Shaft #1	0 to 3 ft	N/A	N/A
7	Soft/soil bottom	Test Shaft #2	30 ft	Entire shaft diameter	100%
8	Tremie breach/cold joint	Test Shaft #2	20.5	N/A	N/A
9	Inclusion in cage interior – 5 sand bags inside cage	Test Shaft #2	12 ft	Shaft center	15%
10	Weak concrete mix	Test Shaft #2	0 to 3 ft	N/A	N/A

The Wisconsin DOT study opted to administer TIP testing using both thermal wires and thermal probes which require installation of access ducts and is more difficult than using wires. The use of the thermal wires is emphasized because they are easier to install and monitor than thermal probes. As a result, thermal wires were used for the test shafts constructed by Wisconsin DOT to test various nondestructive tests. Four TIP wires were incorporated into all of the three (3) test shafts. The TIP wires were manufactured by Pile Dynamics, Inc. (PDI), as was the data acquisition system. The TIP wires include one temperature sensor per foot or 0.3 meter. The wires were affixed to vertical reinforcing bars using plastic cable ties, with one tie between each sensor for most of the wire length. The four wires were affixed to vertical reinforcing bars adjacent to the CSL access tubes, which resulted in approximately equally spaced wires (Boeckmann and Loehr, 2018).

In the Wisconsin DOT study, the thermal probe tests were performed by first dewatering the access ducts and then lowering a temperature probe to the bottom of each access duct. As the probe was lowered, temperature data were measured and recorded, as was the depth of the probe for each

measurement. Depths were automatically recorded using a depth encoder pulley. All of the anomalies were subjected to Levels 1 and 2 analyses (Boeckmann and Loehr, 2018).

ACCEPTANCE CRITERIA FOR CSL AND TIP TESTING IN OTHER STATES

Table 29 summarizes the nondestructive integrity testing and acceptance criteria for drilled shafts that have been proposed in other publications for comparison purposes. Acceptance criteria is important for integrity tests because it illustrates the testing methodology, techniques for interpreting test results, and how to reach a drilled shaft acceptance decision or whether additional action is necessary such as engineering analysis or coring.

Table 29. Drilled Shaft Testing and Acceptance Criteria from CSL and TIP Testing from Various Sources (Boeckmann & Loehr, 2018)

Source	Acceptance Criteria	
	CSL	TIP
ASTM	No specific criteria. "How one applies the results obtained using this standard is beyond its scope."	No specific criteria. "Interpretation ...should contain proper engineering judgment and experience."
Washington State DOT Standard Specifications (2018)	<u>Good</u>: No signal distortion and decrease in signal velocity of 10% or less. <u>Questionable</u>: Minor signal distortion and lower signal amplitude with a decrease in velocity between 10 and 20%. <u>Poor</u>: Severe signal distortion and much lower signal amplitude with a decrease in signal velocity of 20% or more.	<u>Satisfactory</u>: 0 to 6% reduction in effective shaft radius and cover criteria met. <u>Questionable</u>: effective local radius reduction > 6%, effective local average diameter reduction > 4%, or cover criteria not met.
Florida DOT Standard Specifications (2018)	Velocity reduction greater than 30% is not acceptable without 3D tomography and subsequent engineering analysis.	No specific criteria, but requires reports to indicate "unusual temperatures, including cooler local deviations from the average at any depth [or] from the overall average over the entire length." Reports must also include "a conclusion stating whether the tested shaft is free from integrity defects and meets the minimum concrete cover and diameter requirements by the specifications." Thermal modeling (i.e. Level 3 interpretation) is required to satisfy report requirements.

Source	Acceptance Criteria	
	CSL	TIP
Mullins et al. (2009) Draft Specifications for FDOT	N/A	Included two potential criteria, both of which require thermal modeling: (1) "Test results with deviations greater than 5 degrees over a 1 ft length shall be further evaluated using Signal Matching Analyses to determine the possible shaft cross-section loss." (2) "Drilled shafts with either insufficient cover or 5 degree Fahrenheit reduction from the model norm over a length of shaft at least 2 ft in length will not be accepted without an engineering analysis."
Note: Not implemented (per above row)		
	<u>Good:</u> Velocity reduction less than or equal to 10%.	<u>Good:</u> No reduction in effective radius.
Likins and Mullins (2011)	<u>Questionable:</u> Velocity reduction between 11 and 29%.	<u>Questionable:</u> Radius reduction less than or equal to 1 in.
	<u>Poor:</u> Velocity reduction 30% or greater.	<u>Poor:</u> Radius reduction greater than 1 in.
Piscalko et al. (2016) (See also Section 2.6.2)	N/A	<u>Satisfactory:</u> 0 to 6% reduction in effective radius and local cover criteria satisfied. <u>Anomaly:</u> Greater than 6% reduction in effective radius or local cover criteria not satisfied.
Consultant A Documentation (2015)	<u>Good:</u> First Arrival Time (FAT) increase less than 10%; energy reduction less than 6 dB <u>Questionable:</u> FAT increase between 10 and 20%; energy reduction between 6 and 9 dB	N/A

Source	Acceptance Criteria	
	CSL	TIP
	<u>Flaw:</u> FAT increase between 20 and 30%; energy reduction between 9 and 12 dB <u>Defect:</u> FAT increase greater than 30%; energy reduction greater than 12 dB	
PDI Documentation (2017)	N/A	No specific criteria, but requires potential local anomalies be reported. Local anomalies are indicated by “locally low temperatures relative to the average temperature at that depth, or average temperatures significantly lower than the average temperatures at other depths.”
Deep Foundations Institute (2018)	Defines three rating classes graphically based on combinations of FAT increase (%) and energy reduction (dB). Class A ratings are acceptable, Class B ratings are conditionally acceptable, and Class C ratings are highly abnormal.	N/A

REFERENCES

- Adams, J.C., Hajduk, E.L., Halvarsson, P., and Neumann, A., Jr., (2009). "A Case History Evaluation of CSL Access Tube Debonding," Proceedings of International Foundation Congress and Equipment Exposition (IFCEE), Orlando, FL, ASCE, 552-559, <https://ascelibrary.org/doi/pdf/10.1061/41021%28335%2969>.
- Alabama Department of Transportation (ADOT). (2007). "Specifications for Drilled Shaft Construction." Section 506.10(a).
- ASTM Test Method D5882 (2016), "Standard Test Method for Low Strain Impact Integrity Testing of Deep Foundations," ASTM International, West Conshohocken, PA, 2014, DOI: https://compass.astm.org/EDIT/html_annot.cgi?D5882+16.
- ASTM Test Method D6760 (2016), "Standard Test Method for Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing," ASTM International, West Conshohocken, PA, 2014, DOI: 10.1520/ D6760M-16, www.astm.org.
- ASTM Test Method D7949 (2014), "Standard Test Method for Thermal Integrity Profiling of Concrete Deep Foundations," ASTM International, West Conshohocken, PA, 2014, DOI: 10.1520/ D7949M-14, www.astm.org.
- Boeckmann, A. and Loehr, E.J. (2018). "Thermal Integrity Profiling for Detecting Flaws in Drilled Shafts," report prepared for Wisconsin DOT ID no. 0092-16-07, 113 p. Boeckmann, <https://wisconsin.gov/documents2/research/0092-16-07-final-report.pdf>
- Broeckmann, A.Z. and J.E. Loehr (2015), Concrete Mass Pours for Deep Foundations – Synthesis Report, Final Phase I Report to Federal Highway Administration, 81 p.
- Brown, D.A., Turner, J.P., and Castelli, R.J. (2010). "Drilled Shafts: Construction Procedures, and LRFD Design Methods," NHI Course NO. 132014, FHWA NHI-10-016 report, <https://www.fhwa.dot.gov/engineering/geotech/foundations/nhi10016/nhi10016.pdf>.
- CALTRANS. (2015). "Foundation Manual." Issued by Structure Construction.
- Coleman, Travis (2020). Personal communication, GRL, Chicago, Illinois; email: 15 April 2020.
- Davis, A.G. and Hertlien, B.H. (1993), Evaluation of the Integrity of Some Large Concrete Structures Using NDT." American Concrete Institute Spring Convention, Vancouver, March.
- Davis, A.G. and Robertson, S.A. (1976), "Vibration Testing of Piles," Journal of Structural Engineering, June, pp. A7-A10.
- Deep Foundations Institute (DFI) (2019). "Terminology and Evaluation Criteria of Crosshole Sonic Logging (CSL) as applied to Deep Foundations." White Paper, CSL Task Force, Chaired by E. Anna Sellountou, 17 p., <http://www.dfi.org/publications.asp?goto=1058#P1058>.
- Finno, R.J. and Prommer, P.J. (1994). Evaluation on Inaccessible Drilled Shafts Using the Impulse Response Method: Northwestern University, Infrastructure Technology Institute, ITI Publications Directory.
- Hajali, M. and Abishdid, C. (2014). "Cross-hole sonic logging and frequency tomography analysis of

- drilled shaft foundations to better evaluate anomalies locations,” DFI Journal - Journal of the Deep Foundations Institute, 8(1), 27–38. doi: 10.1179/tbc14z.0000000001
- Herne, T.M., Stokoe, K.H., and Reese L.C. (1981). Drilled Shaft Integrity by Wave Propagation Method,” Journal of Geotechnical Engineering, ASCE, Volume 107, No. 10, October, pp. 1327-1344.
- Hollema, D.A. and Olson, L.D. (2002). “Crosshole Sonic Logging and Tomographic Velocity Imaging of a New Drilled Shaft Bridge Foundation,” 8 p., <http://www.olsonengineering.com/wp-content/uploads/ASNT-Tomography-2002.pdf>
- IDOT. (2016). “Illinois Modified ASTM D7949, Method B for TIP Testing of Drilled Shafts, <http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/GBSP92.pdf>.”
- Illinois Department of Transportation (IDOT), (2019). “Crosshole Sonic Logging Testing of Drilled Shafts,” Document GBSP91 revised 9 August 2019 and available at: <http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/GBSP91.pdf>.
- Illinois Department of Transportation (IDOT), (2019). “Thermal Integrity Profile Testing of Drilled Shafts,” Document GBSP92 effective 20 April 2016 2019 and available at: <http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/GBSP92.pdf>.
- Johnson, K.R. (2016). “Analyzing Thermal Integrity Profiling Data for Drilled Shaft Evaluation,” DFI Journal-Journal of the Deep Foundations, Deep Foundations Institute, 10(1), 25-33, DOI: 10.1080/19375247.2016.1169361, <http://dx.doi.org/10.1080/19375247.2016.1169361>.
- Lew, M., Zadoorian, C.J., and Carpenter, L.D. (2002), “Integrity Testing of Drilled Piles for Tall Buildings, Structure,” A joint publication of: National Council of Structural Association; Council of American Structural ; Structural Engineering Institute, October, pp. 14-17.
- Liebich, B.A. (2004). “Acceptance Testing of Drilled Shafts by Gamma-Gamma Logging,” Proceedings of GeoTrans 2004 Specialty Conference, Los Angeles, CA, ASCE, 1200-1208, [https://doi.org/10.1061/40744\(154\)109](https://doi.org/10.1061/40744(154)109).
- Mullins, G. (2010). Thermal integrity profiling of drilled shafts. DFI Journal-The Journal of the Deep Foundations Institute, 4(2), 54-64.
- Mullins, G. and Winters, D. (2011). “Infrared Thermal Integrity Testing Quality Assurance Test Method to Detect Drilled Shaft Defects,” report prepared for Washington DOT ID no. WA-RD 770.1, 176 p. <https://www.wsdot.wa.gov/research/reports/fullreports/770.1.pdf>.
- Mullins, G., and Kranc, S. (2007). “Thermal Integrity Testing of Drilled Shaft – Final Report,” report prepared for Florida DOT ID #BD544-20, 233 p. https://www.pile.com/wp-content/uploads/2017/03/FDOT_BD544_20_rpt.pdf
- O’Neil, M.W. and Reese, L.C., (1999). “Drilled Shafts: Construction Procedures and Design Methods,” Vol. 1, ADSC: International Association of Foundation Drilling, Dallas, TX.

- Ohio DOT. (2019). "Ohio DOT Bridge Design Manual". Section 305.4.6.
- Olson Engineering, Inc. (2006). "Sonic Echo/Impulse Response Testing," 6 p.,
http://www.olsonengineering.com/wp-content/uploads/techbrief_seir_web.pdf
- Paikowsky, S.G. and Chernauskas, L.R. (2003). "Review of Deep Foundations Integrity Testing Methods and Case Histories," Boston Society of Civil (BSCES)-Geo-Institute Deep Foundation Seminar, Paper 18, 30 p.,
<https://pdfs.semanticscholar.org/138d/6ab69b4df3f1caa959e9d67086b15dc63fa2.pdf>
- Paikowsky, S.G., Chernauskas, L.R., Hart, L.J., Ealy, C.D., and DiMillio, A.F. (2000). "Examination of a New Cross-Hole Sonic Logging System for Integrity Testing of Drilled Shafts." Proc. Application of Stress-Wave Theory to Piles, Niyama and Beim editors, Balkema Publishers, Rottendam, ISBN: 90 5809 1503, 8 p.
- Piscsalko, G., Likins, G., and Mullins, G. (2016). "Drilled Shaft Acceptance Based Upon Thermal Integrity Profiling," Proceedings of 41st Deep Foundations Annual Conference, New York, NY, Deep Foundations Institute, 1–10, <https://www.pile.com/wp-content/uploads/2017/03/drilled-shaft-acceptance-criteria-based-upon-thermal-integrity-1.pdf>.
- Sinnreich, J., Canivan, G., and Simpson, R. (2019). "Drilled Shaft Quality Assurance Tools: Interpretation and Impact," Deep Foundations Magazine, Deep Foundations Institute, May-June, 85–89, <http://dfi.dcatalog.com/v/May-June-2019/?page=84>.
- Webster, K., Rausche, F., and Webster, S. (2010). "Pile and Shaft Integrity Test Results, Classification, Acceptance and/or Rejection," TRB 2011 Annual Meeting, Transportation Research Board.

APPENDIX B: COST ANALYSIS

INTRODUCTION

Cost analysis and comparison between the cost of CSL and TIP testing is important for developing recommendations for selecting nondestructive tests for drilled shafts. This data is used to evaluate the cost effectiveness of each test method along with their advantages and disadvantages in order to assess whether the additional advantages of one method are worth the additional investment. A comprehensive cost analysis was conducted for TIP and CSL testing using historical projects that were provided by IDOT. IDOT provided the research team with 28 contracts in which CSL was used with 14 of these projects using the old IDOT pricing method and the other 14 using the new IDOT pricing method. In the old IDOT pricing method, there was only one pay item for CSL testing, which includes the cost of the access ducts, conducting the tests, analyzing the data, and compiling a testing report. In these projects, all of the drilled shafts in a project had CSL access tubes but only a percentage of these drilled shafts were tested and analyzed. In the new IDOT pricing method for CSL, there are two separate pay items for the access ducts, and for the CSL testing, analysis, and reporting. Each IDOT contract number represents a project where TIP or CSL testing was conducted in some or all of the drilled shafts as shown in Table 30 through Table 35.

The cost analysis of TIP and CSL conducted by IDOT is complex because of the different pricing methods and different factors affecting the cost. Some of the other factors affecting the cost of TIP and CSL testing include the volume of drilled shafts tested, number of drilled shafts tested, different contractors, project locations, total drilled shaft volume in a project including the non-tested drilled shafts because even the non-tested drilled shafts have access tubes and/or TIP wires embedded in them. Furthermore, most of this information is either not known, or not collected. Therefore, it was decided to limit the comparison between TIP and CSL testing to: (1) the average cost per one tested drilled shaft per project, and (2) the average costs per cubic yard of concrete of tested drilled shaft per project. These two comparisons were chosen to present a cost overview for IDOT and potentially other engineers that will facilitate estimating costs for future TIP and CSL testing.

Table 30 and Table 31 show details of the cost analysis for the CSL testing using the new IDOT pricing method in the current IDOT CSL specifications. Table 32 and Table 33 present details of the cost analysis for the CSL testing using the old IDOT pricing method in the old CSL specifications. Table 34 and Table 35 show details of the cost analysis for the TIP testing for IDOT TIP projects.

Cost Analysis of CSL Using IDOT's New Pricing Method

Average Costs per One Tested Drilled Shaft per Project

Table 30 shows the bidding information for CSL projects using the new IDOT pricing method in the current IDOT CSL specifications, which includes contract number for each project, letting date, IDOT District Number, total number of drilled shafts constructed, number of drilled shafts tested, total length of drilled shafts with access ducts, unit cost of the access ducts, total CSL access ducts costs, and the average CSL cost per tested drilled shaft. The total CSL access ducts cost is the unit cost of access ducts multiplied by the CSL access ducts quantity. It is important to note that the price per foot

of access duct includes all of the access ducts installed in the shaft, where a shaft with four access ducts does not get 4 times the per foot cost. All information shown in Table 30 were provided by IDOT except for the last two columns, i.e., total CSL access ducts cost and the average CSL cost per tested drilled shaft, which are calculated values. The average CSL cost per tested drilled shaft is equal to the unit cost of CSL testing per one tested drilled shaft plus the total CSL access ducts cost divided by the total number of drilled shafts. The calculation of the average cost per tested drilled shaft is used because the new IDOT pricing method involves installing CSL access ducts in all of the constructed drilled shafts but not necessarily testing all of the drilled shafts. Furthermore, there is a pay item for the CSL access ducts and a separate pay item for the testing, analysis, and reporting of the tested drilled shafts because usually not all drilled shafts are tested. A calculation example is shown below for IDOT contract number 61E18:

Total CSL access duct cost (\$) = unit cost of access ducts (\$/ft) x quantity of CSL access ducts (ft) = \$15/ft x 305 ft= \$4575.00

Average CSL cost per one drilled shaft tested (\$/tested shaft) = unit cost of CSL testing (\$/shaft) + total CSL access ducts cost (\$) / total number of drilled shafts (shafts) = \$6500/shaft + (\$4575/10 shafts) = \$6957.50/shaft

Table 30. Bidding Information for CSL Projects with the New IDOT Pricing

Contract Number	Letting Date	District	Number of Tested Shafts	Unit cost of CSL testing (\$/drilled Shaft)	Total number of shafts	CSL Access Ducts quantity (ft)	Unit cost of Access Ducts (\$/ft)	Total CSL Ducts Cost (\$)	Average CSL Cost per one tested drilled shaft (\$)
61E18	19/1/2018	1	3	6,500.0	10	305.0	15.0	4,575.0	6,957.5
76887	11/9/2018	8	9	1,300.0	36	7,260.0	9.0	65,340.0	3,115.0
60X79	11/9/2018	1	15	3,792.0	64	5,278.0	17.6	92,787.2	5,241.8
60X93	11/9/2018	1	31	3,975.0	78	6,352.0	16.5	104,808.0	5,318.7
68B46	4/26/2019	4	9	2,500.0	84	41,396.0	10.0	413,960.0	7,428.1
78504	1/17/2020	9	16	825.0	22	480.0	47.2	22,641.6	1,854.2
78506	1/17/2020	9	4	1,260.0	4	294.0	47.2	13,868.0	4,727.0
60X99	6/16/2017	1	7	3,500.0	83	6,649.0	40.0	265,960.0	6,704.3
60X75	8/4/2017	1	4	5,000.0	14	1,370.0	18.0	24,660.0	6,761.4
60X76	8/4/2017	1	12	4,000.0	57	4,845.0	20.0	96,900.0	5,700.0
62A74	8/4/2017	1	6	4,000.0	62	540.0	50.0	27,000.0	4,435.5
60X95	11/17/2017	1	10	3,000.0	39	4,051.0	10.0	40,510.0	4,038.7
60X94	6/12/2020	1	19	3,200.0	124	7,666.0	24.0	183,984.0	4,683.7
60W34	11/6/2020	1	8	3,877.0	51	290.0	12.0	3,480.0	3,945.2

Average Costs per Cubic Yard of Concrete of Tested Drilled Shaft per Project

Using the new IDOT pricing method, Table 31 shows the breakdown of the average costs per cubic yard of tested drilled shaft for CSL projects. The calculation example shown below are for IDOT contract number 61E18:

Total volume of all drilled shafts (yd³) = Volume of all drilled shafts in soil (yd³) + volume of all drilled shafts in rock (yd³) = 197 yd³+ 153 yd³= 350 yd³

Total volume of tested drilled shafts (yd³) = Total volume of all drilled shafts (yd³) x number of tested drilled shafts/total number of drilled shafts = 350 yd³ x 3 shafts/10 shafts = 105 yd³

Average volume of one tested drilled shaft (yd³) = Total volume of tested drilled shafts/number of tested drilled shafts = 105 yd³/3 shafts =35 yd³

Average Unit cost of CSL of tested drilled shaft (\$/yd³) = Average CSL cost per tested drilled shaft (\$/shaft)/Average volume of one tested drilled shaft (yd³/shaft) = \$6957.50/35 (yd³) = \$198.79 (\$/yd³)

Average Unit cost of CSL of tested drilled shaft (\$/yd³) = Average CSL cost per tested drilled shaft (\$)/Average volume of one tested drilled shaft (yd³) = \$6957.50/35 yd³ = \$198.79 (\$/yd³)

Table 31. Concrete Volumes and Concrete Prices for CSL Projects with the New IDOT Pricing Method

Contract Number	Volume of all shafts in soil (yd ³)	Volume of all shafts in rock (yd ³)	Total volume of all shafts (yd ³)	Total volume of tested shafts (yd ³)	Average volume of a tested shaft (yd ³)	Average Unit cost of CSL of tested drilled shaft (\$/yd ³)
61E18	197.0	153.0	350.0	105.0	35.0	198.8
76887	929.5	334.6	1,264.1	316.0	35.1	88.7
60X79	5,022.0	5.1	5,027.1	1,178.2	78.6	66.7
60X93	3,889.5	115.3	4,004.8	1,591.7	51.3	103.6
68B46	7,089.6	1,195.2	8,284.8	887.7	98.6	75.3
78504	312.5	130.5	443.0	322.2	20.1	92.1
78506	117.7	14.3	132.0	132.0	33.0	143.2
60X99	3,235.6	43.9	3,279.5	276.6	39.5	169.7
60X75	712.5	17.8	730.3	208.7	52.2	129.6
60X76	5,073.7	0.0	5,073.7	1,068.2	89.0	64.0
62A74	6,244.6	15.0	6,259.6	605.8	101.0	43.9
60X95	1,835.0	42.5	1,877.5	481.4	48.1	83.9
60X94	8,870.0	160.8	9,030.8	1,383.8	72.8	64.3
60W34	93.1	111.4	204.5	32.1	4.0	983.9

Cost Analysis of CSL Using IDOT's Old Pricing Method

Average Costs per One Tested Drilled Shaft per Project

Table 32 shows the bidding information for CSL projects under the old IDOT pricing method. The old IDOT pricing method for CSL testing is only one pay item that includes CSL testing, reports, and the CSL access ducts. Therefore, there are no separate pay items for the access ducts and for CSL testing and reporting as shown in Table 30. Therefore, Table 32 only shows one pay item for CSL (see "Unit cost of CSL (\$/drilled Shaft)" in Table 32). For consistency in this report, another column was created in Table 32 called "Average CSL Cost per tested drilled shaft (\$)" which is similar to the column in Table 30 and essentially has the same values in the column named "Unit cost of CSL (\$/drilled Shaft)". All information shown in Table 32 was provided by IDOT and therefore no calculations were performed to use this data.

Table 32. Bidding Information for CSL Projects with the Old IDOT Pricing Method

Contract Number	Letting Date	District	Number of Tested Shafts	Unit cost of CSL (\$/drilled Shaft)	Total number of shafts	Average CSL Cost per tested drilled shaft (\$)
60L70	1/30/2015	1	23	16,000.0	66	16,000.0
60X07	7/31/2015	1	19	9,500.0	57	9,500.0
60W26	11/8/2013	1	11	8,976.5	40	8,976.5
60W29	2/28/2014	1	4	5,300.0	12	5,300.0
60W71	4/25/2014	1	1	7,000.0	4	7,000.0
60W28	7/11/2014	1	13	5,300.0	22	5,300.0
60W30	3/6/2015	1	4	2,100.0	16	2,100.0
60R95	9/18/2015	1	2	2,100.0	14	2,100.0
62B76	11/18/2011	1	4	10,600.0	7	10,600.0
64G59	9/18/2015	2	32	11,249.9	32	11,249.9
76A91	6/17/2011	8	30	1,500.0	30	1,500.0
76C44	7/30/2010	8	5	10,000.0	17	10,000.0
76C76	7/29/2016	1	3	10,345.0	3	10,345.0
60X78	6/10/2016	1	4	16,300.0	4	16,300.0

Average Costs per Cubic Yard of Concrete of Tested Drilled Shaft per Project

The information shown in Table 33 and its calculations are essentially similar to those shown in Table 31 except, as mentioned previously, that the information in Table 33 is based on the old IDOT pricing method and different projects. Therefore, no calculation examples are shown below for this table because there is only one pay item.

Table 33. Concrete Volumes and Concrete Prices for CSL Projects with the Old IDOT Pricing Method

Contract Number	Volume of all shafts in soil (yd ³)	Volume of all shafts in rock (yd ³)	Total volume of shafts (yd ³)	Total volume of tested shafts (yd ³)	Average volume of a tested shaft (yd ³)	Average Unit cost of CSL of tested drilled shaft (\$/yd ³)
60L70	3,185.1	164.9	3,350.0	1,167.4	50.8	315.2
60X07	2,571.3	122.2	2,693.5	897.8	47.3	201.0
60W26	6,112.7	76.5	6,189.2	1,702.0	154.7	55.5
60W29	1,318.9	38.2	1,357.1	452.4	113.1	46.9
60W71	1,024.0	11.0	1,035.0	258.8	258.8	27.1
60W28	2,708.0	74.0	2,782.0	1,643.9	126.5	41.9
60W30	1,534.0	26.0	1,560.0	390.0	97.5	21.5
60R95	542.0	26.0	568.0	81.1	40.6	51.8
62B76	592.6	10.9	603.5	344.9	86.2	123.0
64G59	3,957.8	690.0	4,647.8	4,647.8	145.2	77.5
76A91	3,058.0	388.0	3,446.0	3,446.0	114.9	13.1
76C44	2,579.0	57.0	2,636.0	775.3	155.1	64.5
76C76	580.4	62.5	642.9	642.9	214.3	48.3
60X78	1,076.0	31.0	1,107.0	1,107.0	276.8	58.9

Cost Analysis of TIP Testing

Average Costs per One Tested Drilled Shaft per Project

There is one main difference between bidding of TIP testing and CSL, which is for TIP there is no cost for access ducts but costs for thermal wires (named “wires” in Table 34 and Table 35) are included. In addition, there is no old and new IDOT pricing methods for TIP testing. This is because TIP testing is a new method to Illinois, and therefore, all of the contract numbers shown in Table 34 are based on the “new” pricing method, which has one pay item for installation of thermal wires and data collection and a second pay item that includes data analysis and report preparation. However, for contract number 64G59 there is a pay item for the wires, but the testing was paid for using an engineering consultant agreement. Therefore, the cost provided for contract number 64G59 represents the total cost of TIP. In addition, project 62J31 called for CSL in the bidding but the contractor bid TIP testing so TIP testing was performed not CSL.

Table 34. Bidding Information for TIP Projects

Contract Number	Letting Date	District	Number of Tested Shafts	Unit cost of TIP testing (\$/drilled Shaft)	Total number of shafts	TIP wires quantity (ft)	Unit cost of wires (\$/ft)	Total TIP wires Cost (\$)	Average TIP Cost per tested drilled shaft (\$)
66A57	11/9/2018	3	8	550.0	8	234.0	85.0	19,890.0	3,036.3
62J31*	11/8/2019	1	9	3,000.0	37	2,775.0	0.3	693.8	3,018.8
95863	1/17/2020	7	16	508.7	16	865.0	42.4	36,667.4	2,800.4
66E70	1/17/2020	3	8	1,425.0	8	108.0	26.0	2,808.0	1,776.0
74180	6/16/2017	7	2	7,500.0	8	304.0	42.0	12,768.0	9,096.0
66A69	11/6/2015	3	20	1,906.4	20	1,224.0	50.0	61,200.0	4,966.4
64G59**	9/18/2015	2	4	13,000.0	32				13,000.0

* Project 62J31 calls for CSL but we believe Contractor bid TIP, planning on requesting a substitution after award of contract.

** Project 64G59 has a pay item for the wires, but the testing was paid for using an engineering Consultant agreement. The number provided represents the total cost for the analysis of the TIP data for all of the shafts.

Average Costs per Cubic Yard of Concrete of Tested Drilled Shaft Per Project

The information shown in Table 35 and its calculations are similar to the information shown in Table 31 except the information shown in Table 35 is for TIP testing with different projects. Therefore, no calculation examples are shown below for Table 35.

Table 35. Concrete Volumes and Concrete Prices for TIP Projects

Contract Number	Volume of all shafts in soil (yd ³)	Volume of all shafts in rock (yd ³)	Total volume of shafts (yd ³)	Total volume of tested shafts (yd ³)	Average volume of a tested shaft (yd ³)	Average Unit cost of TIP of tested drilled shaft (\$/yd ³)
66A57	25.8	24.8	50.6	50.6	6.3	3,036.3
62J31	2,906.1	0.0	2,906.1	706.9	78.5	3,018.8
95863	342.5	140.7	483.2	483.2	30.2	2,800.4
66E69	10.4	12.4	22.8	22.8	2.9	1,776.0
74180	99.6	32.0	131.6	32.9	16.4	9,096.0
66A69	755.0	771.7	1,526.7	1,526.7	76.3	4,966.4
64G59	3,959.7	690.3	4,650.0	581.3	145.3	13,000.0

COMPARISON 1: AVERAGE CSL AND TIP TESTING COSTS PER ONE TESTED DRILLED SHAFT PER PROJECT

In this report, there are two methods used to compare the CSL and TIP testing costs, which are: (1) comparing the average cost of integrity testing per one tested drilled shaft per project and (2) comparing the average cost of integrity testing per one cubic yard of concrete of tested drilled shaft per project. Therefore, Figure 48 shows the TIP and CSL costs per one tested drilled shaft versus average tested drilled shaft volume per project. Figure 48 also shows that the comparison was made using the average volume of one tested drilled shaft per project on the x-axis. This was selected because the average volume of one tested drilled shaft would indicate the length and/or diameter of the tested drilled shafts, which is an important factor for the pay items.

The first important observation about the plot in Figure 48 is that there is a large scatter of the data, where the average cost of CSL ranges between less than \$2,000 to larger than \$16,000, and the average cost of TIP ranges between less than \$2,000 to larger than \$13,000 with a limited number of TIP projects compared to the number of CSL projects. Figure 48 shows that the TIP and CSL trendlines are similar, which reflects similar costs. These trendlines were chosen to be power function trendlines because they provided the smoothest curvature for the available data. However, other trendline functions were examined and they did not provide a smooth shaped trendline probably due to the large scatter in the data shown in Figure 48. Nevertheless, it is important to mention that due to the large data scatter, the trendlines should be used as an indication of the overall general cost of integrity testing and not as a correlation or cost estimation tool.

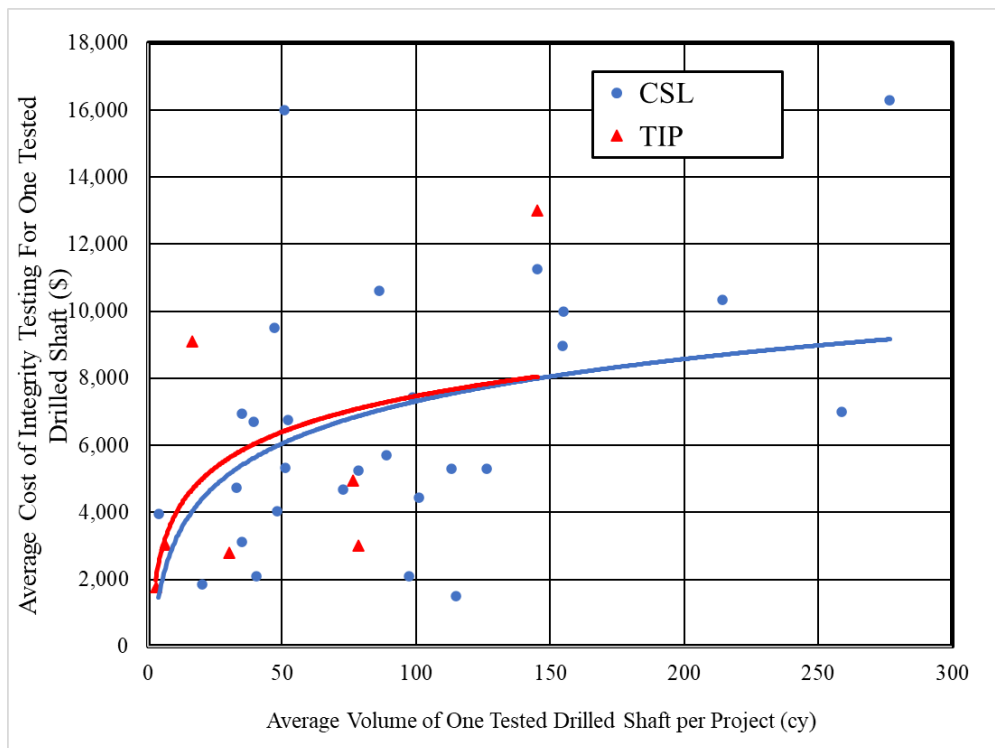


Figure 48. Graph. TIP and CSL costs per one tested shaft versus average volume of one tested drilled shaft per project including only IDOT data.

COMPARISON 2: AVERAGE CSL AND TIP TESTING COSTS PER YD³ OF CONCRETE OF ONE TESTED DRILLED SHAFT PER PROJECT

Figure 49 is similar to Figure 48 except Figure 49 is plotted using the average cost of integrity testing per cubic yard of concrete for one tested drilled shaft instead of the average cost of integrity testing per one tested drilled shaft as in Figure 48. Figure 49 shows the TIP/CSL costs per yd³ of a tested drilled shaft versus average tested drilled shaft volume per project. The scatter in this figure is less than that in Figure 48 and the general trend of TIP and CSL data is the average cost per yd³ is inversely proportional to the average volume of one tested drilled shaft. This reduction increases rapidly up to about an average volume of one tested drilled shaft of about 30 yd³, where after this volume, the reduction in average cost of integrity testing per yd³ is smooth and gradually decreases with increasing the average volume of one tested drilled shaft. Figure 49 shows that the TIP and CSL trendlines become similar indicating that both integrity testing methods have costs that are comparable.

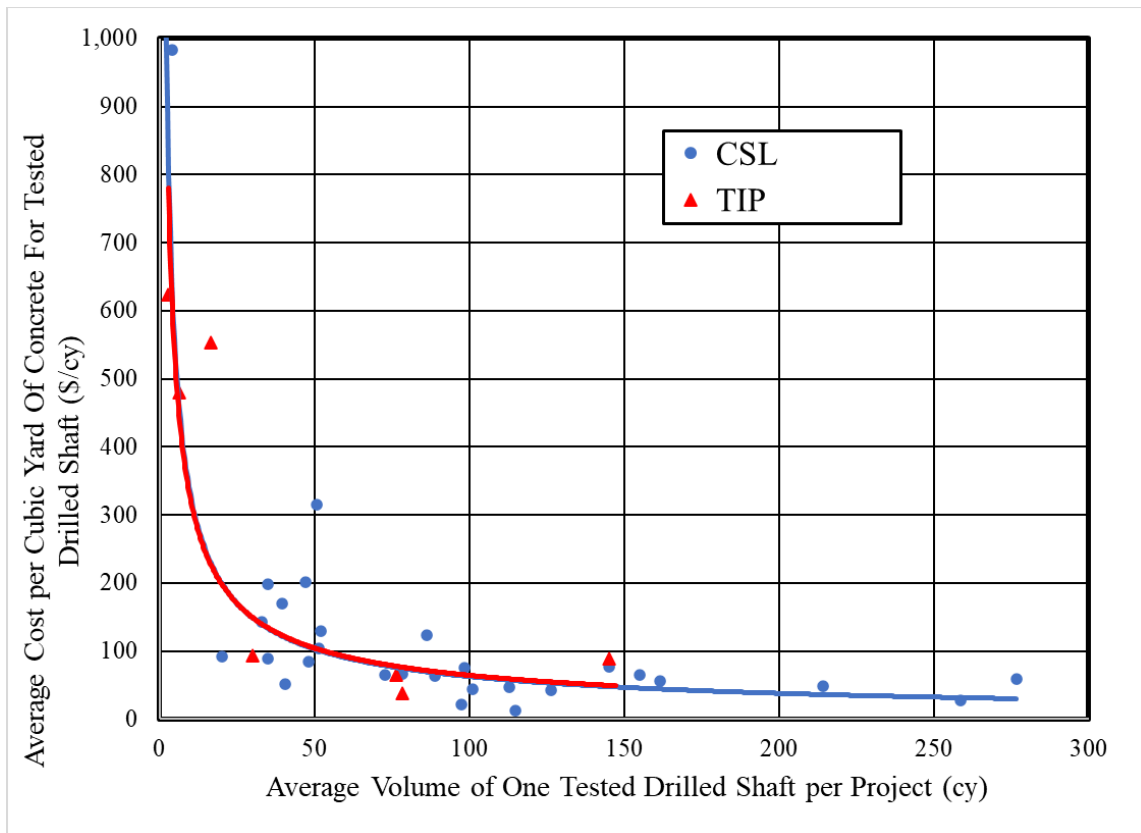


Figure 49. Graph. TIP and CSL costs per cubic yard of a tested shaft versus average volume of one tested drilled shaft per project including only IDOT data.

SUMMARY

A comprehensive analysis of TIP and CSL costs was performed in this appendix. The data provided by IDOT is for 7 TIP projects and 28 CSL projects, where 14 of the 28 CSL projects were awarded based on the new IDOT pricing method and the other 14 based on the old IDOT pricing method. The comparison between TIP and CSL costs was examined using: (1) The average volume of one tested drilled shaft and the average cost of integrity testing for one tested drilled shaft, and (2) The average volume of one tested drilled shaft and the average cost of integrity testing per yd^3 of concrete of tested drilled shaft.

Figure 48 which is plotted with the average cost of one tested drilled shaft shows the general trend that integrity testing cost increases with increasing the average volume of one tested drilled shaft. While Figure 49 which is plotted with the average cost of integrity testing per one yd^3 of a tested drilled shaft shows that the unit cost of integrity testing per yd^3 decreases with increasing average volume of one tested drilled shaft.

In general, TIP and CSL costs are comparable but there are differences based on a case by cases basis. These figures should provide IDOT and other states with a general idea or a guideline when for estimating integrity testing costs based on project volume, drilled shaft volume, and total average drilled shaft cost.

APPENDIX C: TEST DRILLED SHAFT #1

SITE INVESTIGATION

Test drilled shaft #1 is located in the highway median along Interstate 72 in Macon County near Decatur, Illinois as shown in Figure 50.



Figure 50. Photo. Location of test drilled shaft #1 in Macon County, Illinois along the highway median along Interstate 72.

One soil boring was conducted using a hollow stem auger and a split spoon sampler on May 16th, 2019 as shown in Figure 51 and Figure 52. The ground surface elevation is 688.51 ft. The standard penetration test (SPT) blow count every twelve inches (N value) is 13, 15, 14, 15, 17, 18, 15, 22, 15, 17, 13, 7, 23, 13, and 13 and range from 7 and 23. The unconfined compression strength and the moisture content range between 0.2 tsf to 5.15 tsf and between 9% to 24%, respectively. The soil encountered is hard stiff to very stiff grey clay to dark grey clay from the ground surface to depth of 29.5 ft, brown silty clay loam from depth of 29.5 ft to 34.5 ft, soft brown sandy loam from depth of

34.5 ft to 39.5 ft, and stiff to very stiff grey clay till from depth of 39.5 ft to 51 ft. The first encounter of the ground water was at elevation of 654 ft (depth of 34.5 ft), upon completion of soil boring, the elevation of the ground water was at elevation 658.5 ft (depth of 30 ft), and after 24 hours, the elevation of the ground water was at 664 ft (depth of 24.5 ft).

 Illinois Department of Transportation Division of Highways IDOT		SOIL BORING LOG				Page <u>1</u> of <u>2</u>
ROUTE <u>I-72</u> DESCRIPTION <u>ICT R27-188 Evaluating the Accuracy & Use of Drilled Shaft Integrity Methods in Illinois</u>		LOGGED BY <u>E. Sandschafer</u>				
SECTION <u>Median</u> LOCATION <u>I-72 Median, SEC. 21, TWP. 17N, RNG. 2E, 3 PM</u>		Date <u>5/16/19</u>				
COUNTY <u>Macon</u> DRILLING METHOD <u>Hollow stem auger & split spoon</u> HAMMER TYPE <u>Auto 140#</u>						
STRUCT. NO. <u>Test Shaft</u> Station <u>W 88.984421, N 39.907873</u>	D E P T H B L O W S U C S M O I S T	Surface Water Elev. <u>N/A</u> ft Stream Bed Elev. <u>N/A</u> ft Groundwater Elev.: <u>First Encounter</u> <u>654.0</u> ft <u>Upon Completion</u> <u>658.5</u> ft <u>After 24 Hrs.</u> <u>664.0</u> ft	D E P T H B L O W S U C S M O I S T	Groundwater Elev.: <u>First Encounter</u> <u>654.0</u> ft <u>Upon Completion</u> <u>658.5</u> ft <u>After 24 Hrs.</u> <u>664.0</u> ft	Ground Surface Elev. <u>688.51</u>	
BORING NO. <u>B-1</u> Station <u>W 88.984421, N 39.907873</u> Offset <u>0.0ft</u> Ground Surface Elev. <u>688.51</u>	(ft) /6" (tsf) (%)	(ft) /6" (tsf) (%)	(ft) /6" (tsf) (%)	(ft) /6" (tsf) (%)	(ft) /6" (tsf) (%)	
3" Topsoil / 688.26 Brown CLAY Embankment Hard, moist Brown & grey marbled Grey Very stiff Hard Very stiff	4 5 8 6 -5 6 9 5 6 8 5 -10 6 9 5 6 11 4 -15 8 10 5 5 10 9 -20	4.50 PP 4.12 B 4.74 B 4.33 B 2.27 B 4.12 B 3.92 B 	10 12 10 11 9 12 	1.75 PP 5.15 B 2.27 B 2.47 B 0.74 B 0.20 PP 3	11 11 24 23 24 11 	

Figure 51. Illustration. Soil Boring log #1 of test drilled shaft #1.



Illinois Department of Transportation

Division of Highways
IDOT

SOIL BORING LOG

Page 2 of 2

Date 5/16/19

ROUTE I-72 DESCRIPTION ICT R27-188 Evaluating the Accuracy & Use of Drilled Shaft Integrity Methods in Illinois LOGGED BY E. Sandschafer

SECTION Median LOCATION I-72 Median, SEC. 21, TWP. 17N, RNG. 2E, 3 PM

COUNTY Macon DRILLING METHOD Hollow stem auger & split spoon HAMMER TYPE Auto 140#

STRUCT. NO. Test Shaft
Station W 88.984421, N 39.907873

BORING NO. B-1
Station W 88.984421, N 39.907873
Offset 0.0ft
Ground Surface Elev. 688.51

D E P T H (ft)	B L O W S (ft)	U C S Qu (tsf)	M O I S T (%)
6	2.89	13	
9	B		
3			
6	1.48	13	
7	B		
2			
4	2.68	13	
9	B		

Surface Water Elev. N/A ft
Stream Bed Elev. N/A ft
Groundwater Elev.:
First Encounter 654.0 ft
Upon Completion 658.5 ft
After 24 Hrs. 664.0 ft

Very Stiff, moist, grey, CLAY TILL
Sample swelled

Stiff

Very stiff (continued)

637.51

Extent of Exploration

Benchmark: TBM Point #500, IP
on Top of Mt. Macon.

Figure 52. Illustration. Soil Boring log #2 of test drilled shaft #1.

TEMPERATURE AT THE REBAR CAGE FOR AN IDEAL SHAFT

Figure 53 shows the 3D temperature profile model for drilled shafts after Johnson (2016) with black and red arrows added to show the temperature at the rebar cage of test drilled shaft #1. In this figure, the x-axis shows the radial position where the zero value is the center of the drilled shaft and the negative values shows the temperature to the right side from the center and the positive values shows the left side from the center. The z-axis shows the drilled shaft radius, and the y-axis shows the temperature at the peak of cement hydration. For test drilled shaft #1, the diameter of the drilled shaft is 4 ft, the rebar cage diameter is 3.5 ft with a 1.75 ft radial position from the center of the drilled shaft. Applying the dimensions of test drilled shaft #1 as shown in Figure 53 leads to an expected peak temperature of 150 °F at the rebar cage.

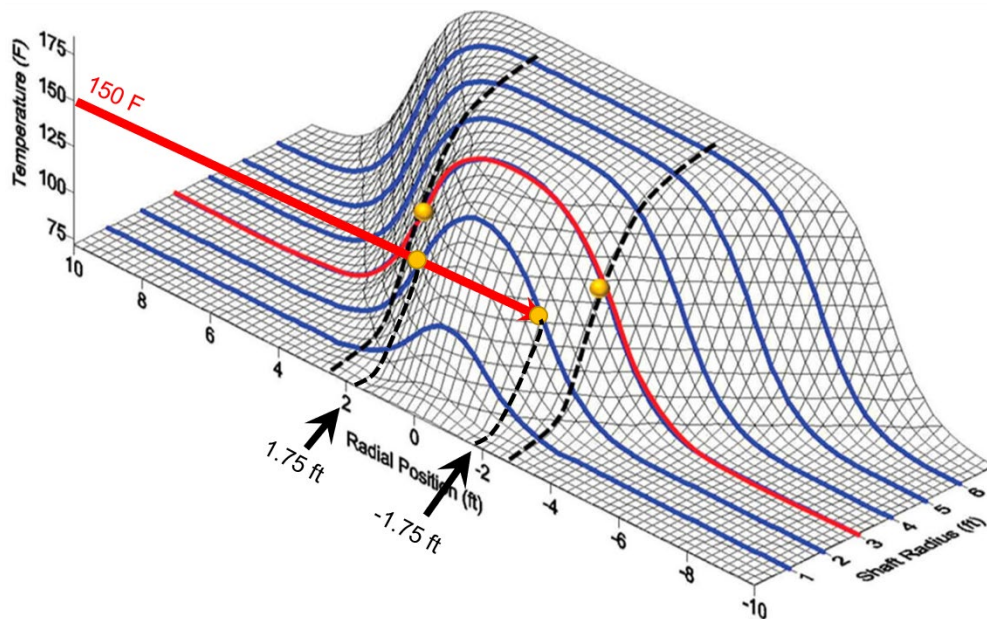


Figure 53. 3D graph. 3D temperature profile model for drilled shafts with black and red arrows added to show the temperature at the rebar cage of test drilled shaft #1 (after Johnson, 2016).

Figure 54 shows the 2D temperature profile model for drilled shafts after Mullins (1997) with red arrows added to show the temperature at the rebar cage. In this figure, only the radial position on the x-axis and the peak temperature on the y-axis are shown. However, different curves are drawn in this figure for drilled shafts with different diameters. The blue line curve in Figure 54 is for a 4 ft diameter drilled shaft, and therefore, the red arrows inserted in this figure show that for a radial position of 1.75 ft (rebar cage diameter of 3.5 ft), the peak temperature should be 122 °F. Using the two different methods of estimating the concrete temperature provides a range of 122 °F to 150 °F, which is too large to be considered reliable.

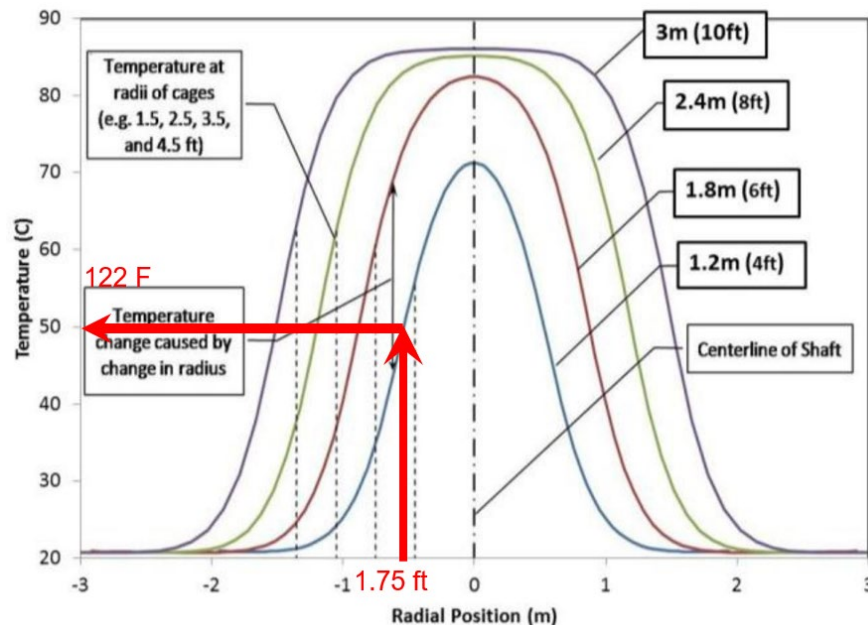


Figure 54. Graph. 2D temperature profile model for drilled shafts with red arrows added to show the temperature at the rebar cage of test drilled shaft #1 (after Mullins, 1997).

CONSULTANT A'S TIP RESULTS

Consultant A's Results for test drilled shaft #1 include the thermal integrity testing results that are presented in Figure 55 through Figure 57 showing the measured temperatures (Fahrenheit degrees) vs. depth (ft) at different times after placement. Figure 58(a) presents the estimated effective radius vs. depth. The roll-off in temperature at the top is caused by heat loss due to the concrete/air interface at the ground surface. The roll-off in temperature at the bottom is caused by heat loss due to the concrete/soil interface at the bottom of drilled shaft. A 3-D interpretation of the tested drilled shaft is presented in Figure 58(b). In general, temperature variations of ± 0.9 degrees Fahrenheit are within normal range for TIP results due to the accuracy of the sensor. Anomalies would be indicated by abrupt reductions in temperature at a particular depth. The radius calculations performed by Consultant A were based on the measured thermal profile and the placed concrete volume noted above. The generated 3-D profile is based on data from all thermal wire cables attached to the reinforcing cage. The measured thermal profiles present the measured temperature versus depth for each active sensor at the selected time interval.

Consultant A's interpretation is that the effective average radius is oversized relative to the reported casing diameter of 54 in. from the top of concrete to a depth of 7 ft. A reduction in the effective radius was found at the bottom of the temporary casing as the drilled shaft transitions from cased to uncased. The drilled shaft is modeled as oversized from the top of concrete to a depth of 27 ft (see Figure 58[b]). There are two reductions in the effective drilled shaft radius indicated at 28 and 33 ft below the drilled shaft top as shown in Figure 58(b). The reduction at 28 ft is most evident in Wires 1 and 4, evident to a lesser extent in Wire 3, and not evident in Wire 2 (see Figure 56[a]). Figure 56(a) shows that the reduction at 32 ft is evident in all four wires. There is a bulge from 33 to 40 ft below the drilled shaft top, which coincides with the granular layer identified in the provided soil boring in

Figure 51. Below 40 ft there is a significant reduction in effective radius, which is shown in all wires. Consultant A's TIP model indicates the effective radius is less than the cage radius from 44 ft below the drilled shaft top to the bottom of the reinforcing cage.

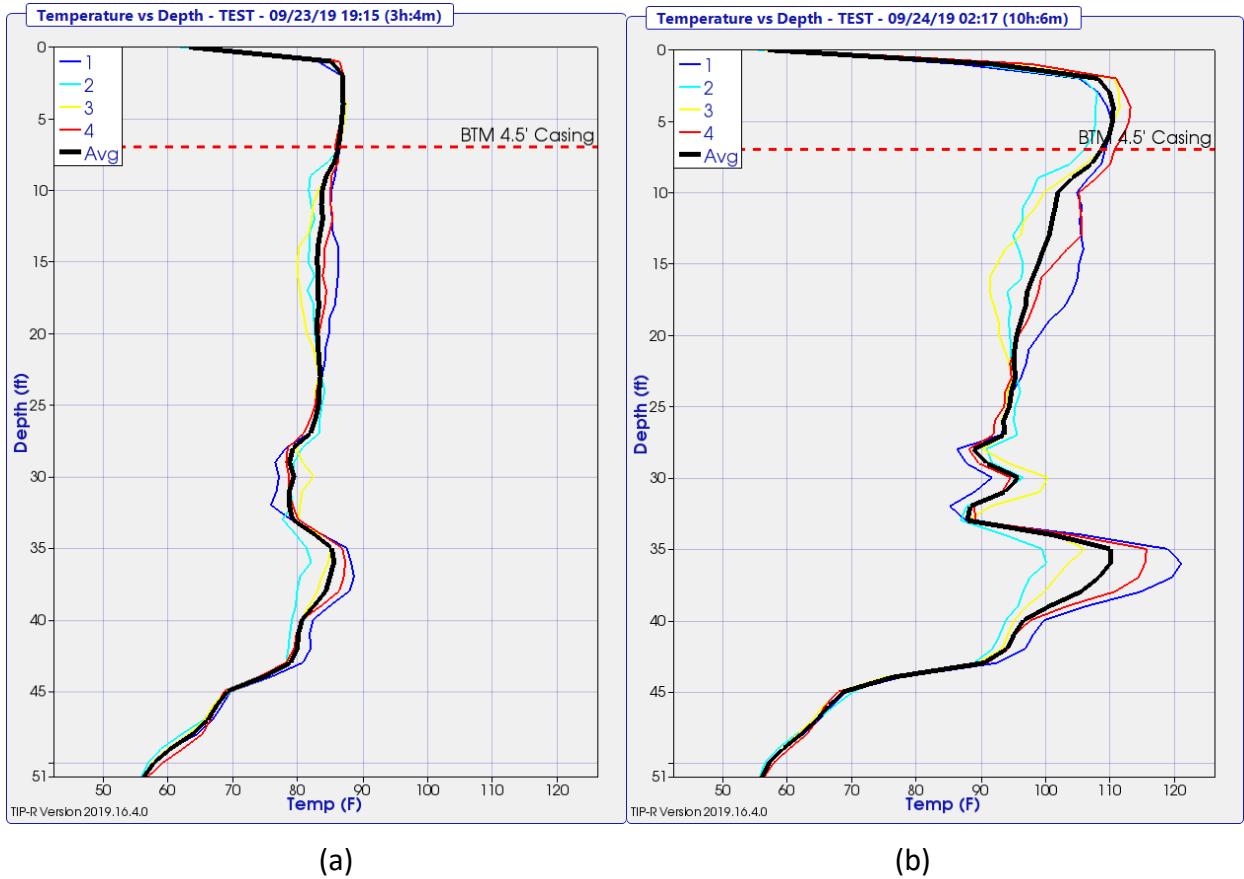


Figure 55. Graph. Temperature versus depth profile for the 4 wires in test drilled shaft #1: (a) at 3h 4m, and (b) at 10h 6m after concrete placement.

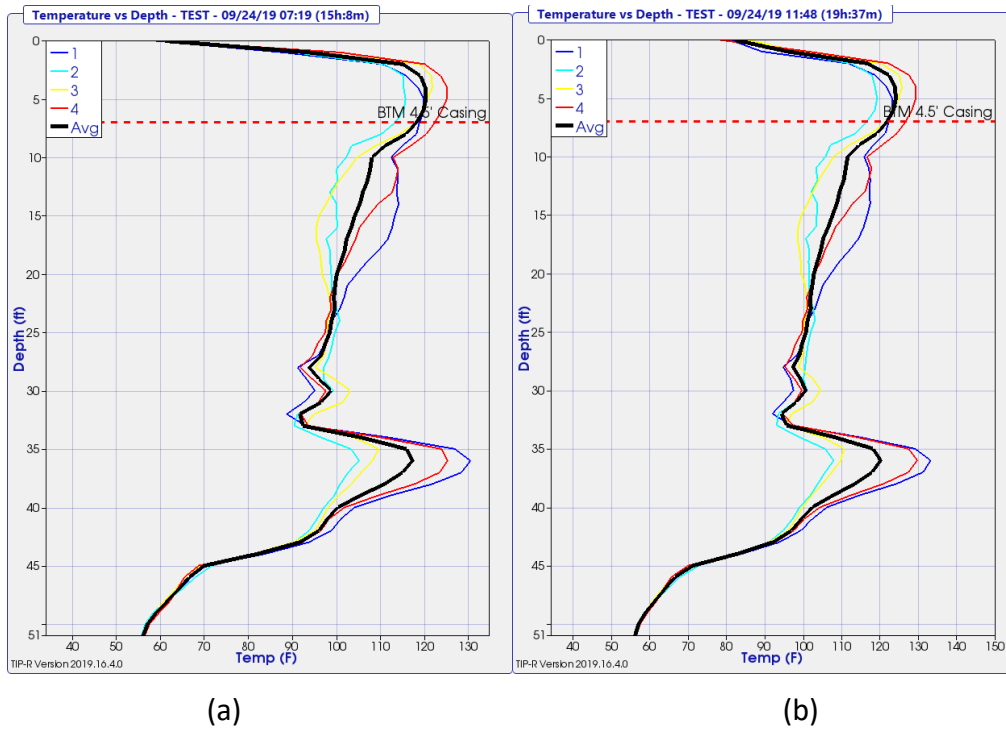


Figure 56. Graph. Temperature versus depth profile for the 4 wires in test drilled shaft #1: (a) at 15h 8m, and (b) at 19h 37m after concrete placement.

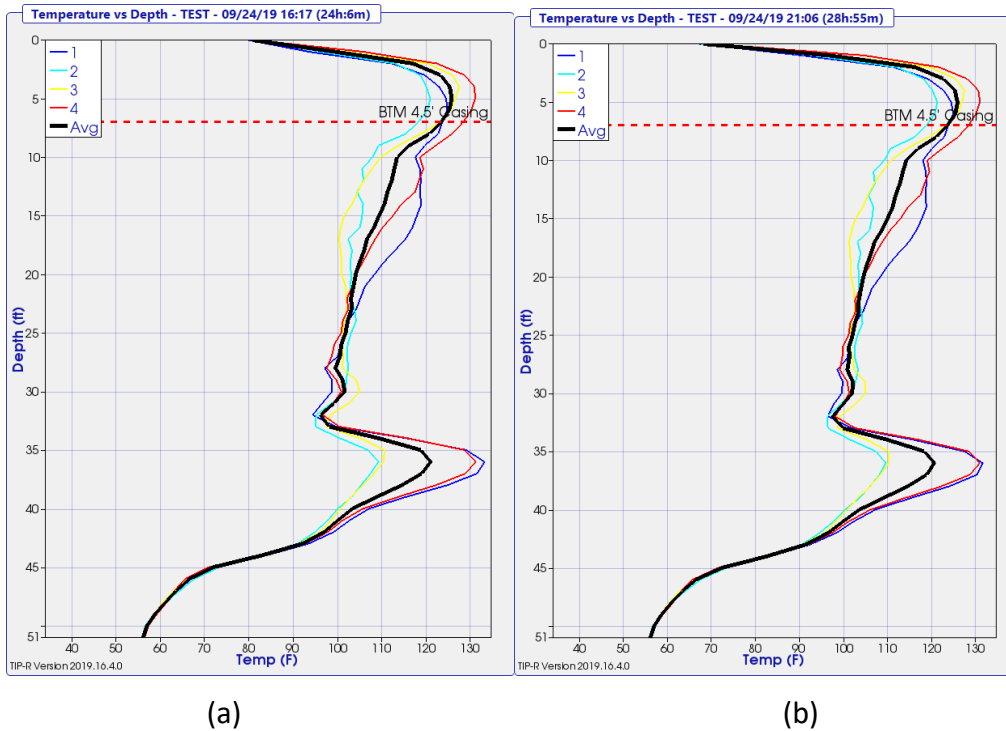


Figure 57. Graph. Temperature versus depth profile for the 4 wires in test drilled shaft #1: (a) at 24h 6m, and (b) at 28h 55m after concrete placement.

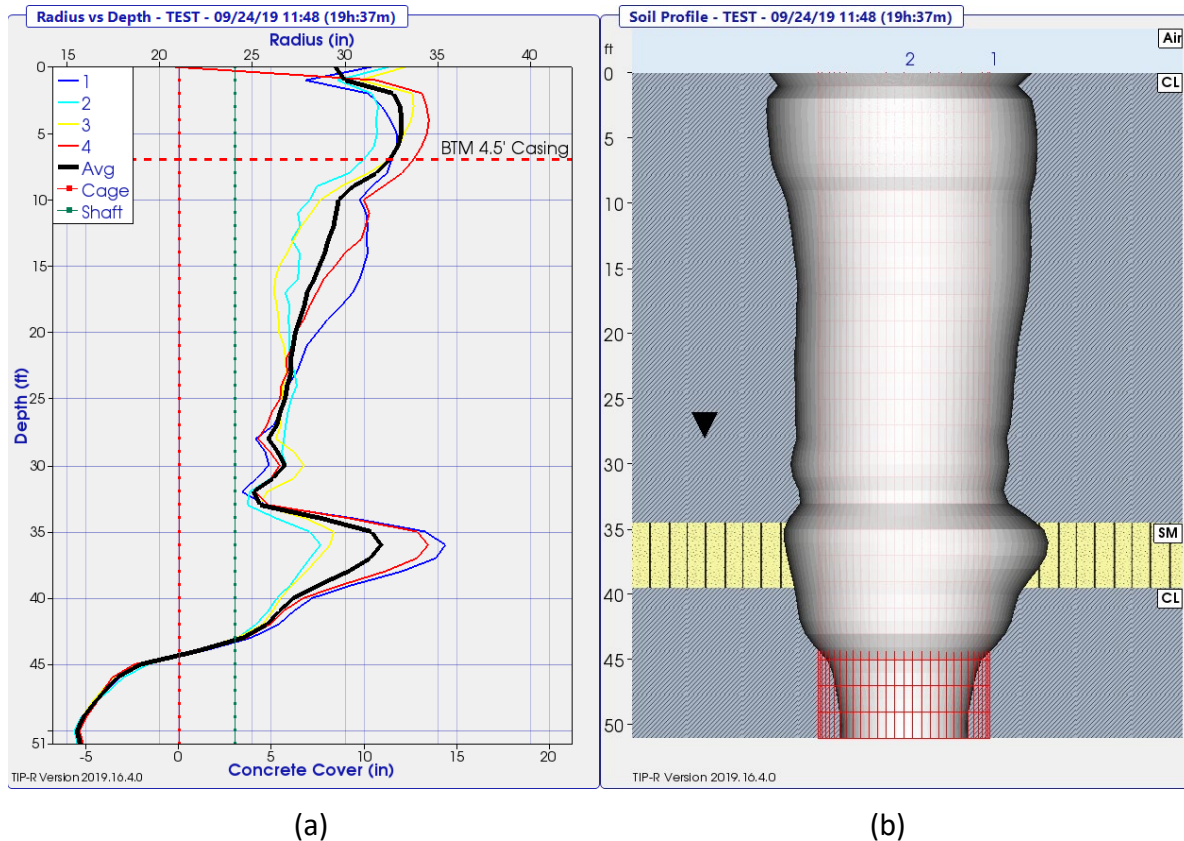


Figure 58. Graph. (a) radius versus depth and Illustration. (b) 3D rendering with rebar cage and soil type for the 4 wires in test drilled shaft #1.

To further evaluate the integrity at the bottom of test drilled shaft #1, Consultant A plotted the theoretical vs placed concrete volume based on the reported depths at the end of each concrete truck as shown in Figure 59. The placed concrete volume is deficient of the theoretical volume within the measurements recorded for the first concrete truck (see the depth at 35 ft in Figure 59), which includes a portion of the drilled shaft with a bulge. Consultant A also included time versus temperature plots for specific depths in Figure 60 (a) through Figure 62 (b). The curves are as expected to a depth of 37 ft (see Figure 60 and Figure 61(a)) and begin to show a reduction in temperature shortly after placement at a depth of 43 ft (see Figure 61(b)). The curves at 46 and 49 ft show a general decrease in temperature following placement as shown in Figure 62.

The TIP model can over-predict the effective radius in instances where areas of complete section loss occur. The model shown in Figure 58 (b) indicates the effective radius is less than the cage radius near the drilled shaft bottom, but still shows a positive value for the effective radius. Based on the temperatures indicated in Figure 62, the lower five feet of the drilled shaft have essentially zero heat generation from cementitious material from the time of placement to time of peak temperature. Given all the available information, Consultant A noted that the effective radius is over-predicted in the bottom five feet in the TIP model.

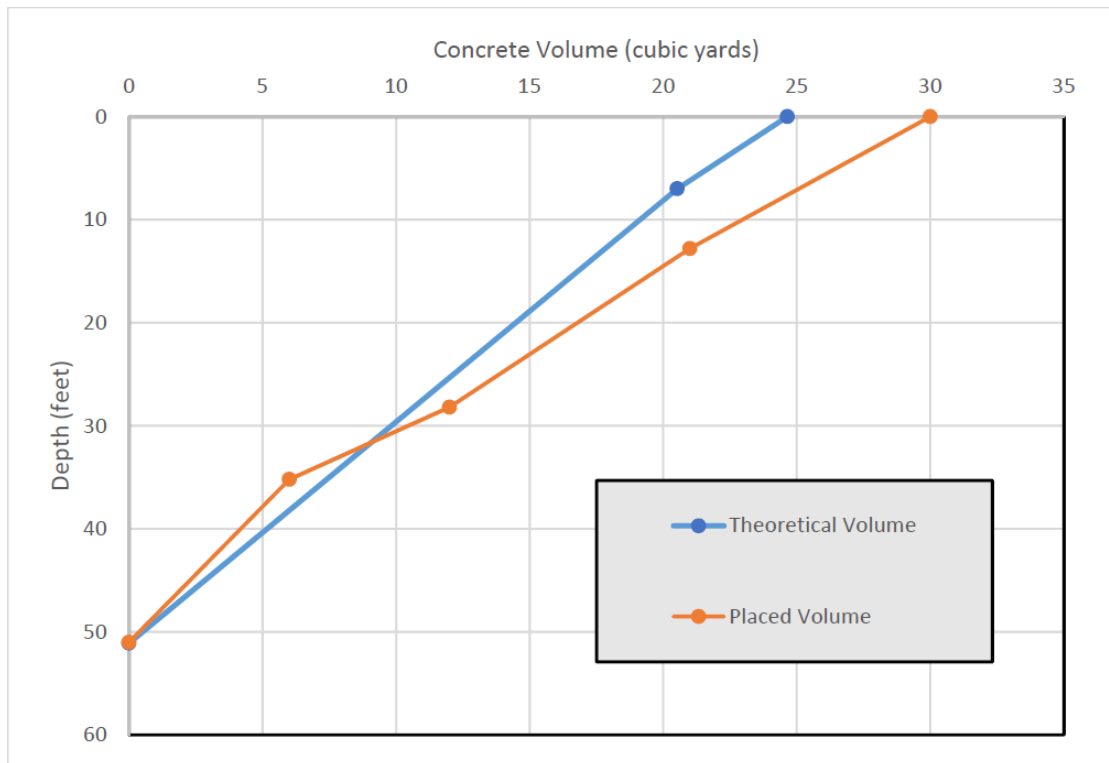


Figure 59. Graph. Theoretical vs. Placed Concrete Volume in test drilled shaft #1.

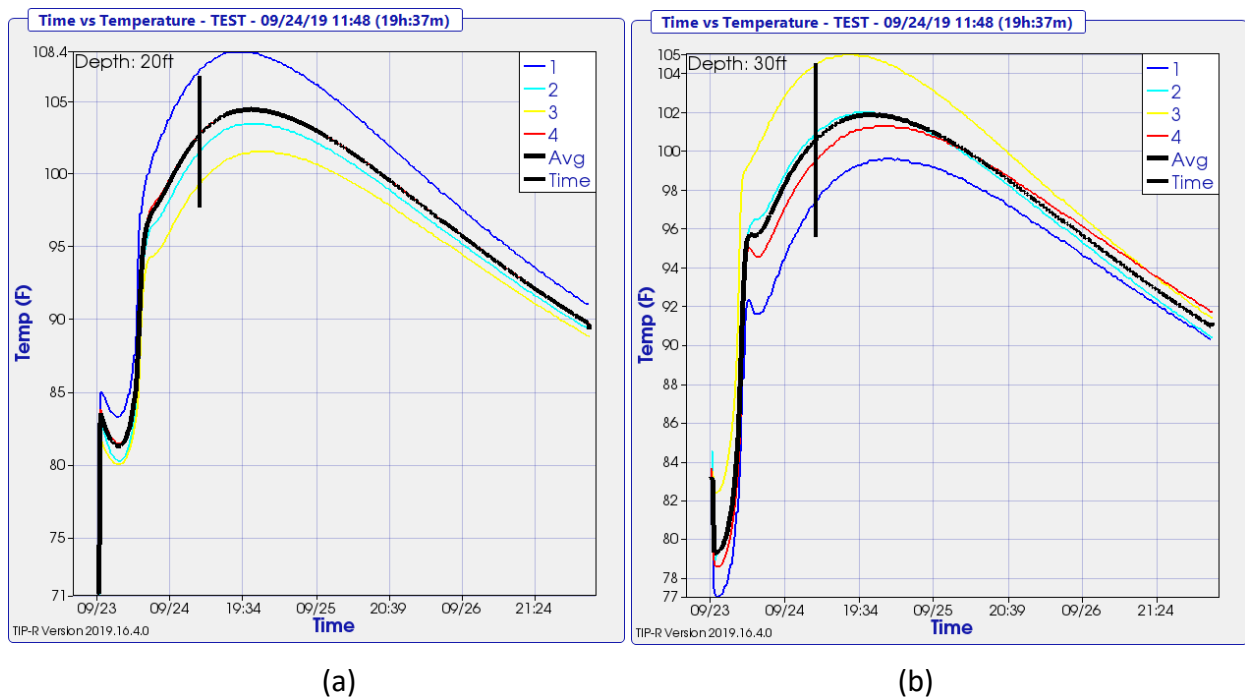


Figure 60. Graph. Time versus temperature at: (a) 20 ft and (b) 30 ft in test drilled shaft #1.

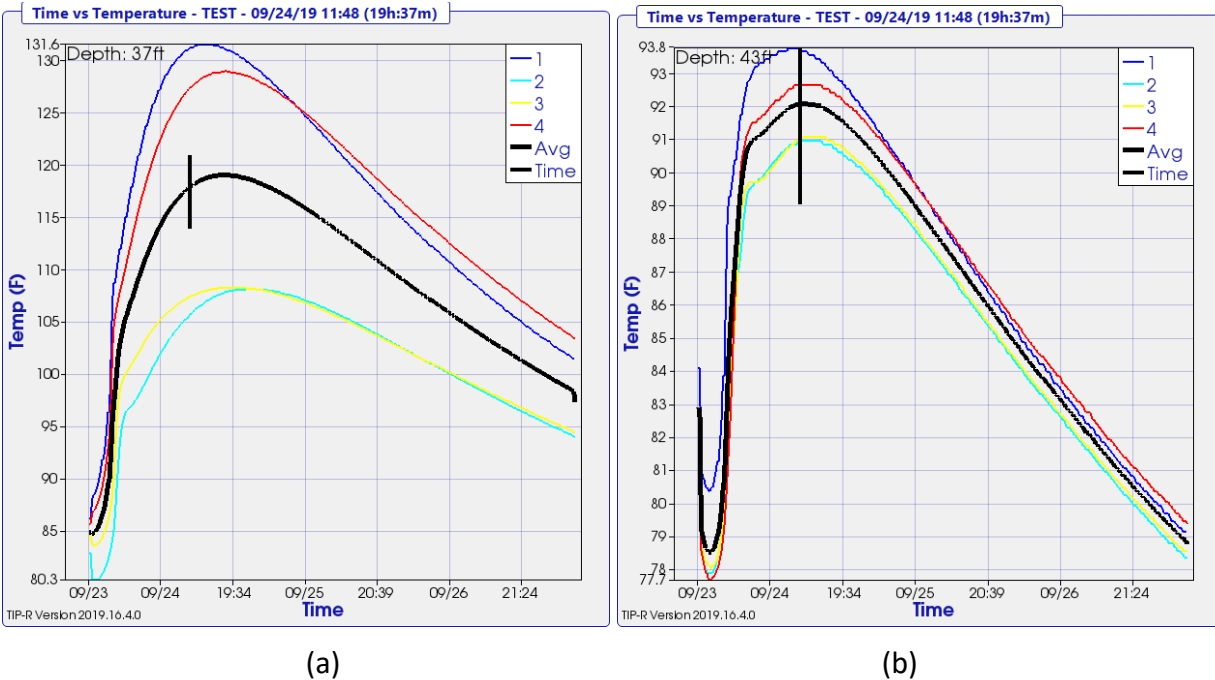


Figure 61. Graph. Time versus temperature at: (a) 37 ft and (b) 43 ft in test drilled shaft #1.

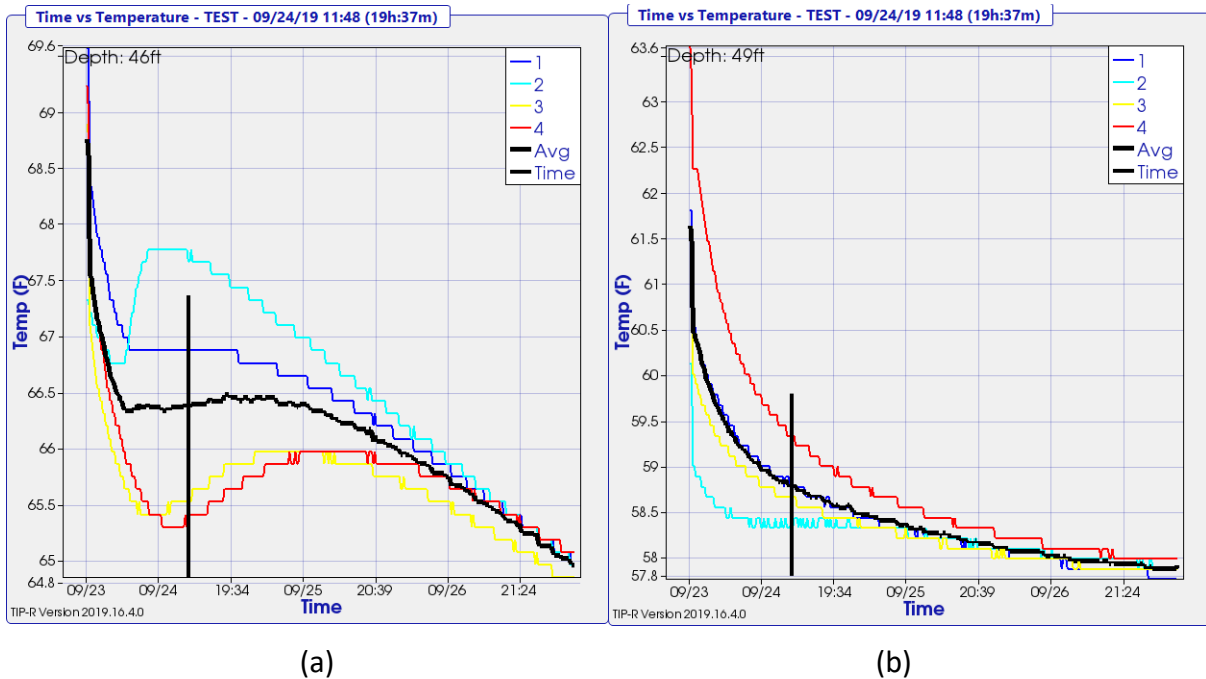


Figure 62. Graph. Time versus temperature at: (a) 46 ft and (b) 49 ft in test drilled shaft #1.

SHAPE

Figure 63 shows SHAPE specifications. Figure 64 through Figure 68 show the profiles for sensor view 5-1 (Figure 64), sensor view 6-2 (see Figure 65), sensor view 7-3 (see Figure 66), sensor view 8-4 (see

Figure 67), and the maximum eccentricity profile which is sensor view 7-3 (see Figure 68). Figure 64 shows that the drilled shaft from the left side is shifted and the actual drilled shaft hole is not aligned with the designed size. Figure 65 shows that the drilled shaft hole is aligned with the planned drilled shaft size. Figure 66 and Figure 67 show that the right side of the drilled shaft hole is shifted. This misalignment between the actual drilled shaft hole geometry and the designed drilled shaft geometry is about 0.3 ft for all the different sensor views. Figure 69 show the maximum eccentricity plan view in test drilled shaft #1 which is 0.02 ft. The increase in concrete volume could be due to the collapse of the drilled shaft sidewall consisting of a weak sandy soil after performing the SHAPE and SQUID testing. SHAPE results shown herein found that the diameter at the top and at the bottom of the shaft is 4 ft and 3 ft, respectively, which is less than the 4 ft diameter of the auger used to drill the shaft.



SHAPE Specifications

October 2017

*PATENT PENDING

SHAPE Body

Size: 558 x 457 mm (22 x 18 inches)
 Weight: 31.75 Kg (70 lbs.)
 Material: Stainless Steel and Aluminum
 Standard Kelly Bar Connection Sizes: 101.6 mm (4 in), 152.4 mm (6 in), 203.2 mm (8 in)
 Temperature Range: -20 to +55°C Operating; -40 to +85°C Storage
 Winch deployment system available upon request

SHAPE Tablet

Size: 320 X 250 X 68 mm (12.6 x 9.8 x 2.7 inches)
 Weight: 5 Kg (11 lbs.)
 Temperature range: 0 to 40°C operating; -20 to 65°C storage
 Display: 26.4cm (10.4"), sunlight readable, resolution 1024 X 768; capacitive touch screen
 Video Outputs: HDMI, VGA
 Battery Power: 4 hour continuous data collection 12 V battery + back-up battery standard
 Charging time: 6 Hours max; 120/240 charger input voltage
 Operating System: Microsoft Windows® 7 or higher
 Data storage and ports: 60 GB or larger SSD internal drive; Ethernet port; 4 USB ports
 Optional external accessories: USB keyboard and mouse
 Remote Operation: SHAPE Tablet is equipped for high speed internet access and remote operation
 Technical support: SHAPE Tablet is equipped for remote error checking and updating
 Units of operation: Traditional US, SI, or Metric
 Full one-year warranty on parts and labor

30725 Aurora Road • Cleveland, Ohio 44139 USA • +1-216-831-6131 • Fax +1-216-831-0916
 E-mail: info@pile.com • www.pile.com

A-3

Figure 63. Text. SHAPE specifications.

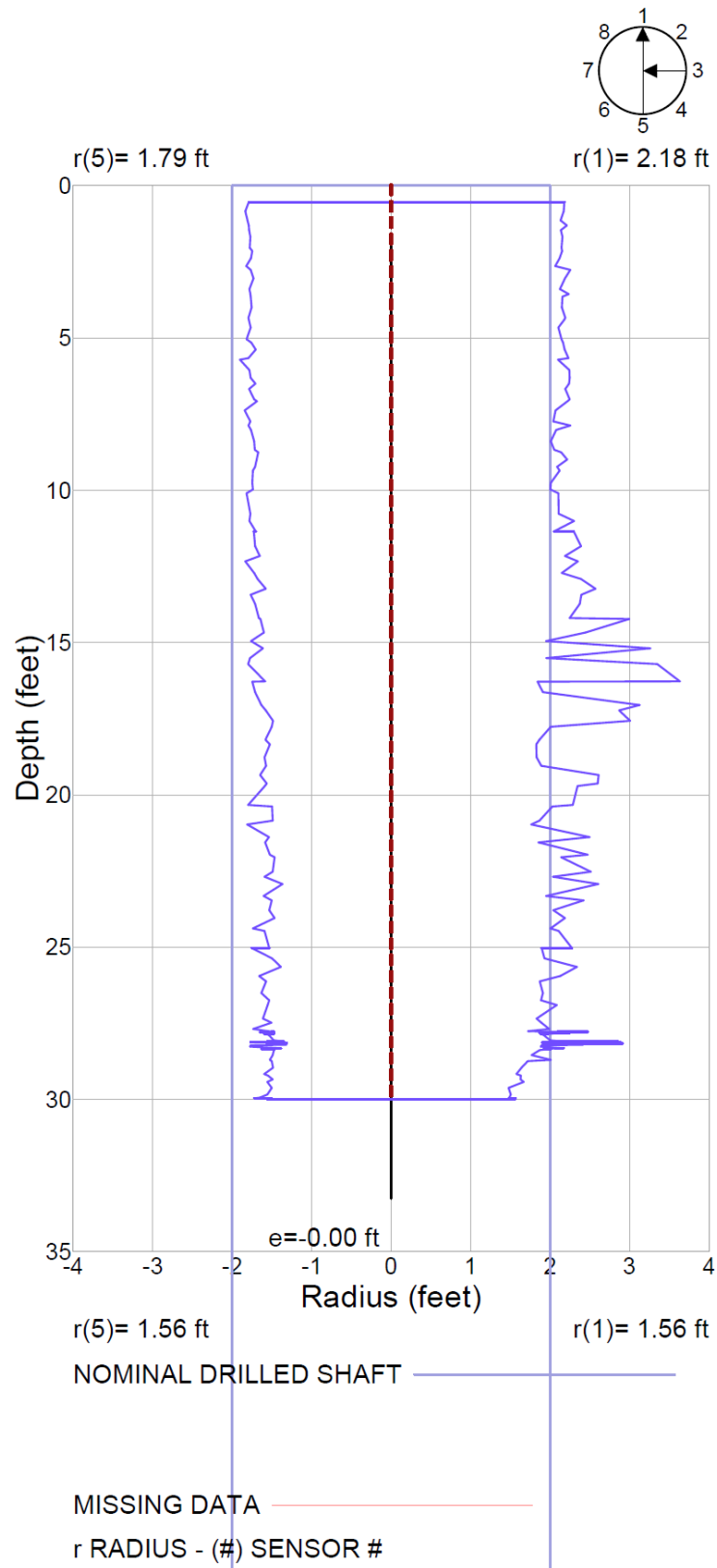


Figure 64. Graph. SHAPE results for sensor view 5-1 in test drilled shaft #1.

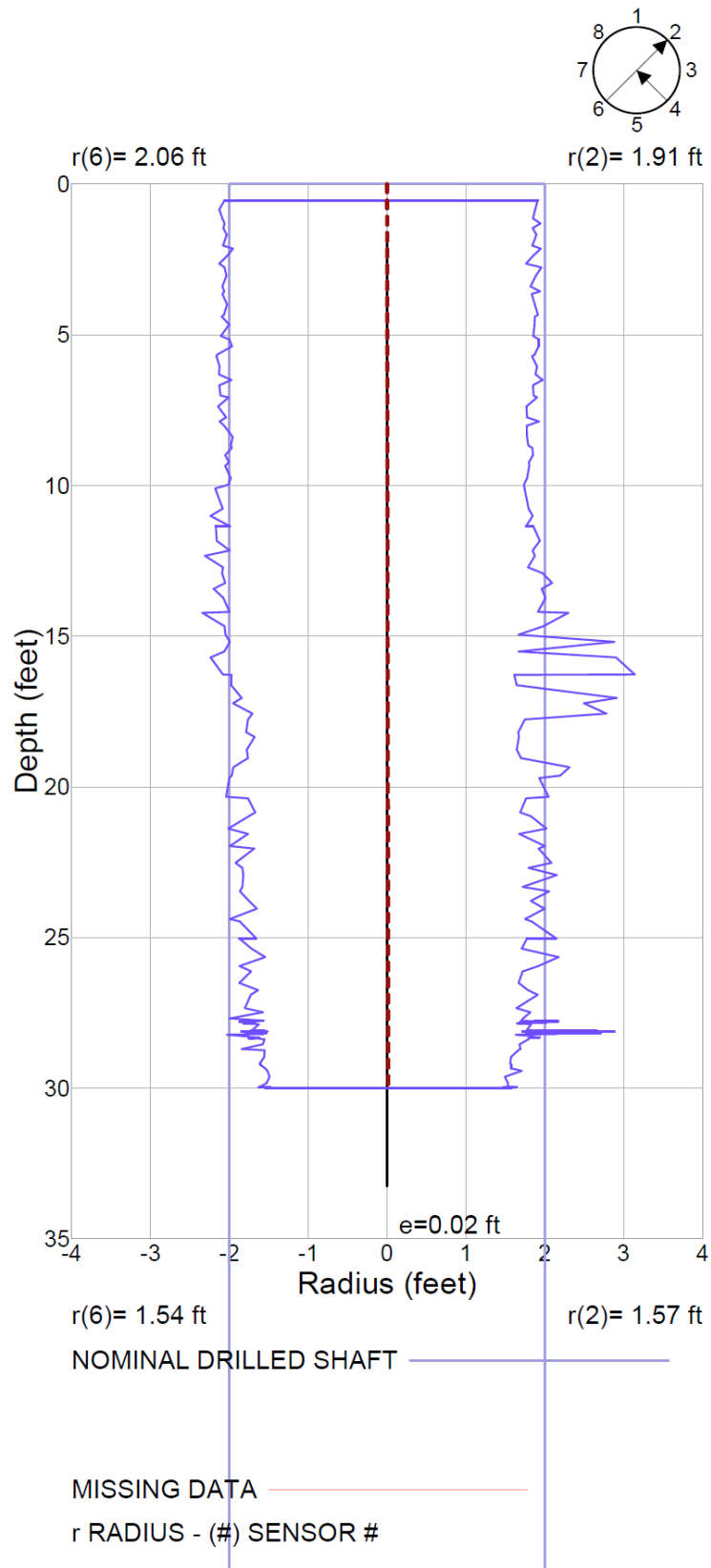


Figure 65. Graph. SHAPE results for sensor view 6-2 in test drilled shaft #1.

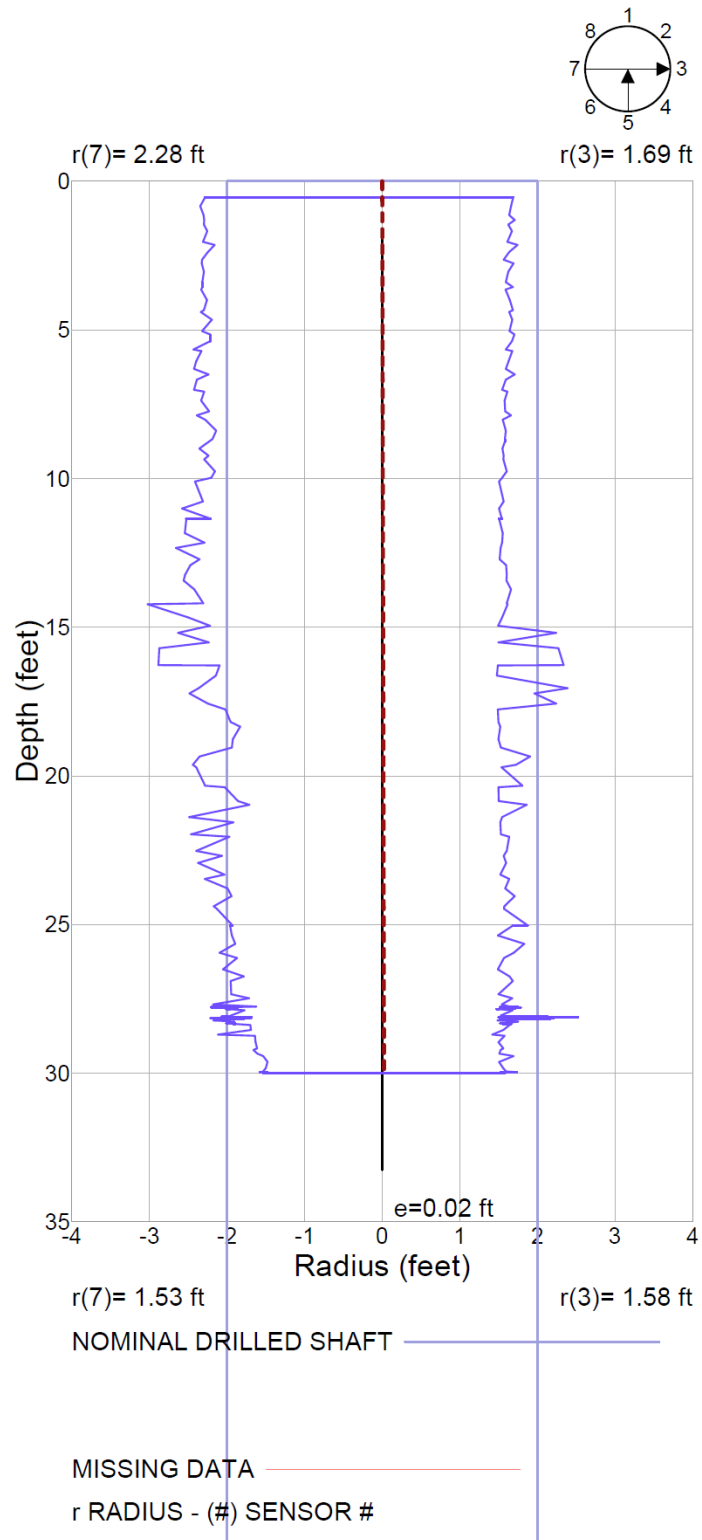


Figure 66. Graph. SHAPE results for sensor view 7-3 in test drilled shaft #1.

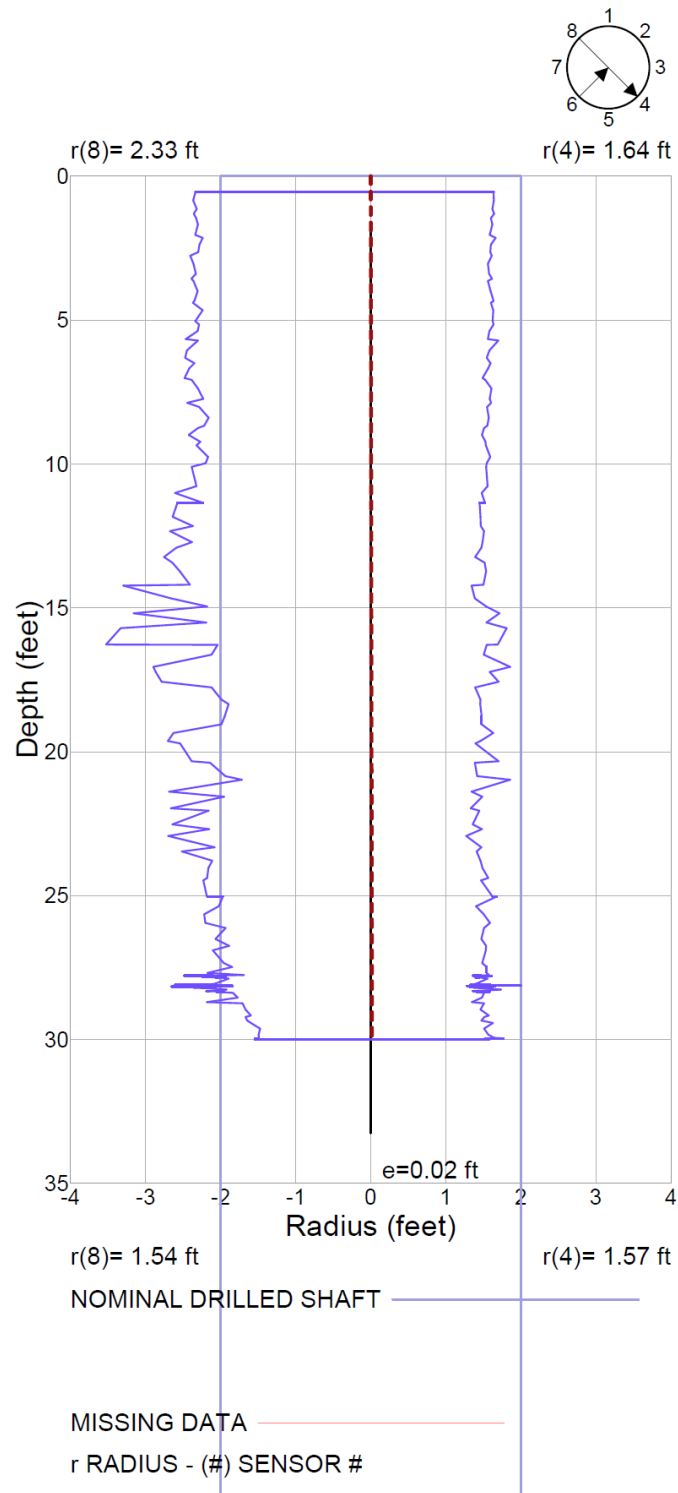


Figure 67. Graph. SHAPE results for sensor view 8-4 in test drilled shaft #1.

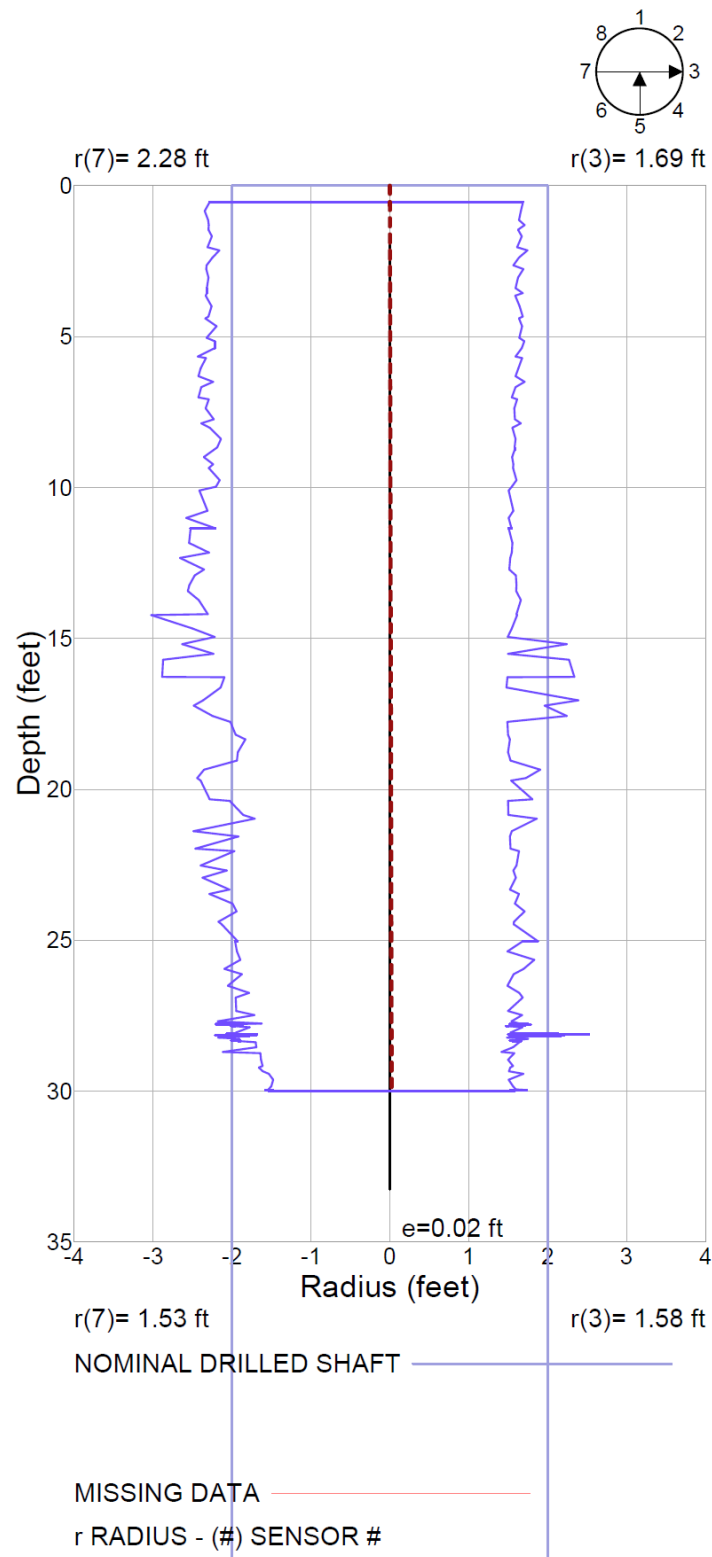
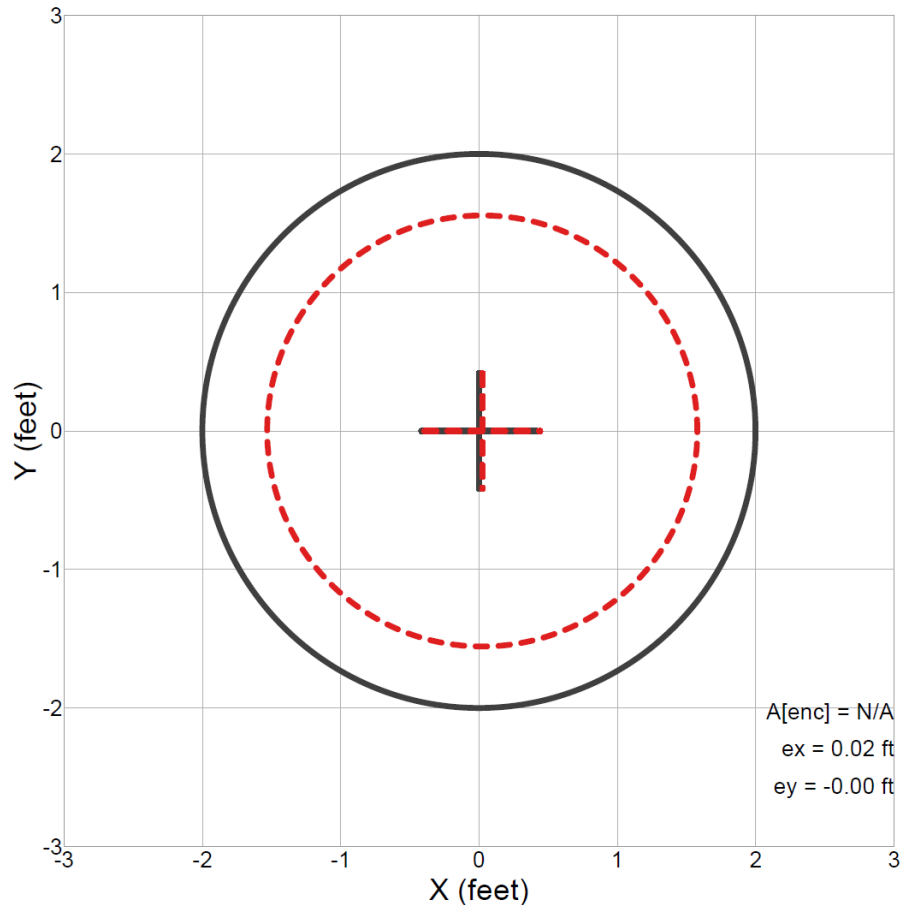


Figure 68. Graph. SHAPE results for the maximum eccentricity profile in test drilled shaft #1.

BEARING = 90.0 degrees
 OFFSET = 0.02 feet
 LENGTH = 30.00 feet
 VERTICALITY = 0.08 %%
 ECCENTRICITY: ex = 0.02, ey = -0.00 feet



Measured Diameter at the Top —————
 Measured Diameter at the Bottom
 A[enc] = Encroachment Area

Figure 69. Graph. SHAPE results for the maximum eccentricity plan view in test drilled shaft #1.

SQUID

Figure 70 shows the SQUID specifications. Testing was performed two times at one location at the bottom of the drilled shaft in the center. For each test (referred to as run), data is collected from 3 penetrometers and 3 displacement plates providing 3 force vs. displacement graphs for each run as shown in Figure 71 and Figure 72 for run #1 and #2, respectively. These curves are evaluated for clay

and gravel thickness by calculating the displacement between two thresholds. The lower threshold is called the debris threshold (DTH) and is set at 20 lbs of force. The upper threshold called the penetrometer threshold (PTH) is set at 160 lbs of force. These values are based on the criteria proposed by Moghaddam et al., (2018), and recommended by the manufacturer. Figure 71 shows that the clay and gravel thickness ranges between 3.27 inches to 4.71 inches, while Figure 72 shows that the clay and gravel thickness ranges between 0.25 inches to 0.76 inches.



Quality Assurance for Deep Foundations

Shaft Quantitative Inspection Device* (SQUID) Specifications

February 2016

SQUID Body

Size (height x hexagon largest diagonal): 629 x 647 mm (24.75 x 25.5 inches)
 Weight (including penetrometers and contact plates): 188 kg (415 lbs)
 Material: Stainless Steel and Aluminum
 Standard Kelly bar connection sizes: 101.6 mm² (4 in²), 152.4 mm² (6 in²), 203.2 mm² (8 in²)
 Cable Length: 61 m (200 ft) standard; 152m (500ft) cable length optional
 Temperature Range: -20 to 55°C operating; -40 to +85°C Storage
 Applied force limit: 135 kN (30 kips)

SQUID Penetrometers

Material: Stainless Steel
 Number of penetrometers: 3 standard
 Penetrometer tip: area 10 cm² (1.55 in²) standard, larger tips optional; replaceable
 Maximum penetrometer pressure: 100 MPa (14 ksi/2000 ksf)
 Penetrometer pressure measurement resolution: 0.1 MPa (14 psi/2 ksf)
 Maximum depth of penetration: 150 mm (6 in)

SQUID Contact Plate(s)

Size: 152 mm (6 in) OD; 46 mm (1.8 inch) ID; thickness 25.4 mm (1 inch)
 Weight each contact plate assembly: in air 6.75 kg (14.9 lbs); in water: 5.85 kg (12.9 lbs)
 Contact Plate pressure (free to move): in air 4 kPa (0.58 psi/0.083 ksf); in water 3.5 kPa (0.50 psi/0.072 ksf)
 Contact plate displacement measurement resolution: 0.004 mm (0.0002")
 Maximum contact plate movement: 150 mm (6 in)

Wireless Transmitter

Transmission Range: 100m
 Frequency: 2.4 GHz
 Output power: 18 dBm
 Mounting: On cable reel
 Temperature Range: -10 to 55°C operating; -20 to 70°C storage

SQUID Tablet

Size: 320 X 250 X 68 mm (12.6 x 9.8 x 2.7 inches)
 Weight: 5 Kg (11 lbs.)
 Temperature range: 0 to 40°C operating; -20 to 65°C storage
 Display: 26.4cm (10.4"), sunlight readable, resolution 1024 X 768; capacitive touch screen
 Video Outputs: HDMI, VGA
 Battery Power: 4 hour continuous data collection 12 V battery + back-up battery standard
 Charging time: 6 Hours max; 120/240 charger input voltage
 Operating System: Microsoft Windows® 7
 Data storage and ports: 60 GB SSD internal drive; Ethernet port; 4 USB ports
 Optional external accessories: USB keyboard and mouse
 Remote Operation: SQUID Tablet is equipped for high speed internet access and remote operation
 Technical support: SQUID Tablet is equipped for remote error checking and updating
 Units of operation: Traditional US, SI, or Metric
 Full one year warranty on parts and labor

*Patent Pending

A-6

30725 Aurora Road • Cleveland, Ohio 44139 USA • +1-216-831-6131 • Fax +1-216-831-0916
 E-mail: info@pile.com • www.pile.com

Figure 70. Text. SQUID specifications.

Project: DECATUR TEST SHAFT

Location: CENTER

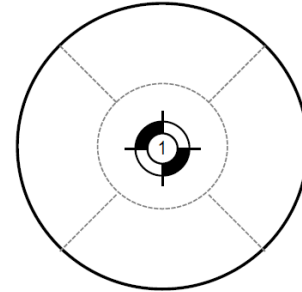
Shaft: TEST1

Test number: 1 **Run number:** 1

Tester's Name: TRB

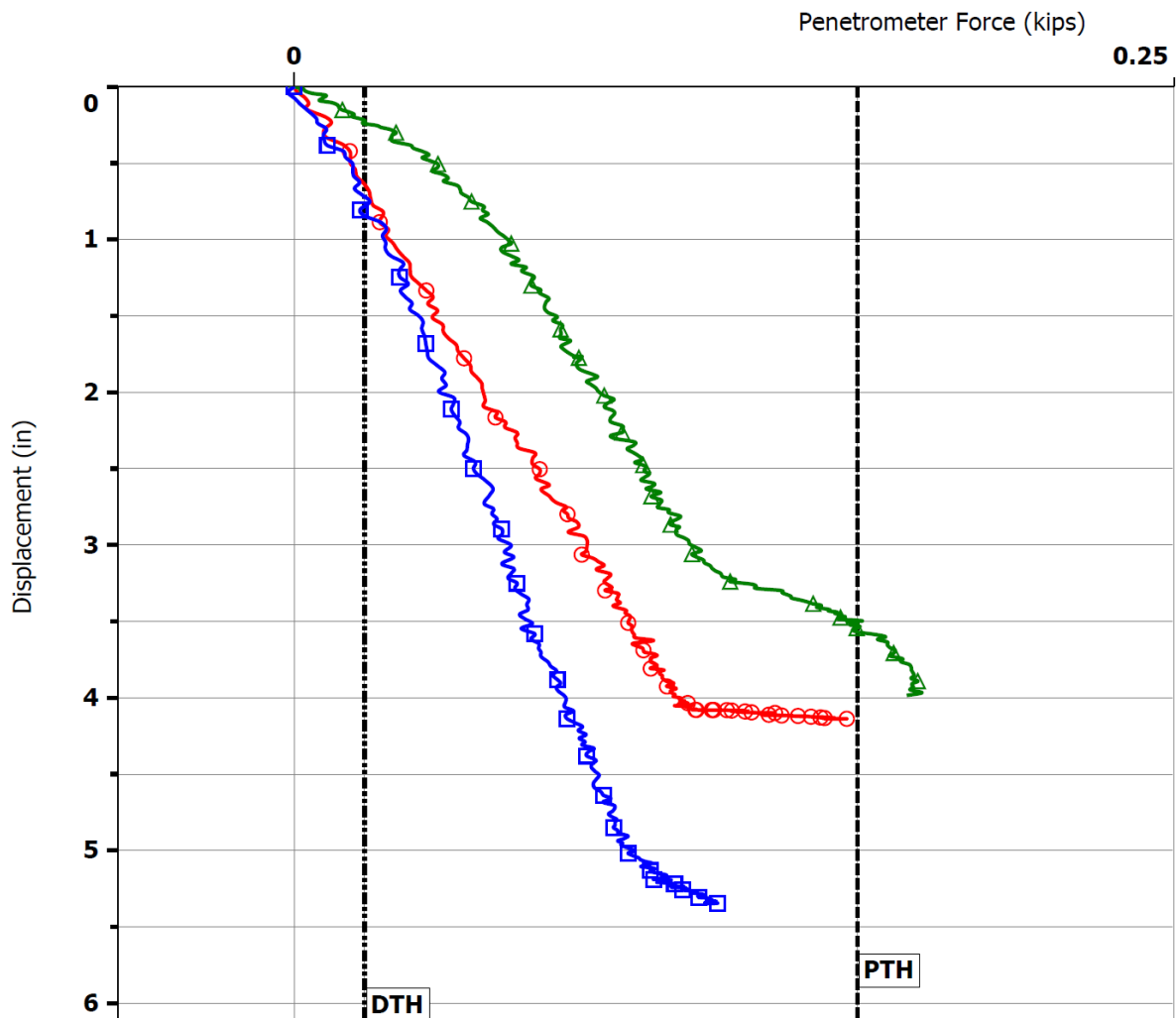
Test Table

Flat Tip penetrometers	30016DC	30022DC	30015DC
Disp. at 0.160 kips (in)		3.49	
Disp. at 0.020 kips (in)	0.64	0.22	0.72
Debris thickness (in)	> 3.53	3.27	> 4.71



Collected Time: 9/23/2019 1:20:54 PM

30016DC 30022DC 30015DC



SQUID-S Version 0.9.4.1
© 2019, Pile Dynamics, Inc.



Figure 71. Graph. SQUID results for test drilled shaft #1 with defects' locations (run number 1).

Project: DECATUR TEST SHAFT

Location: CENTER

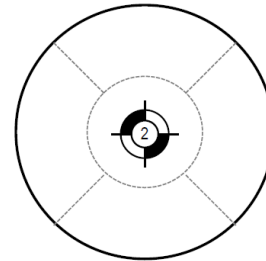
Shaft: TEST1

Test number: 1 **Run number:** 2

Tester's Name: TRB

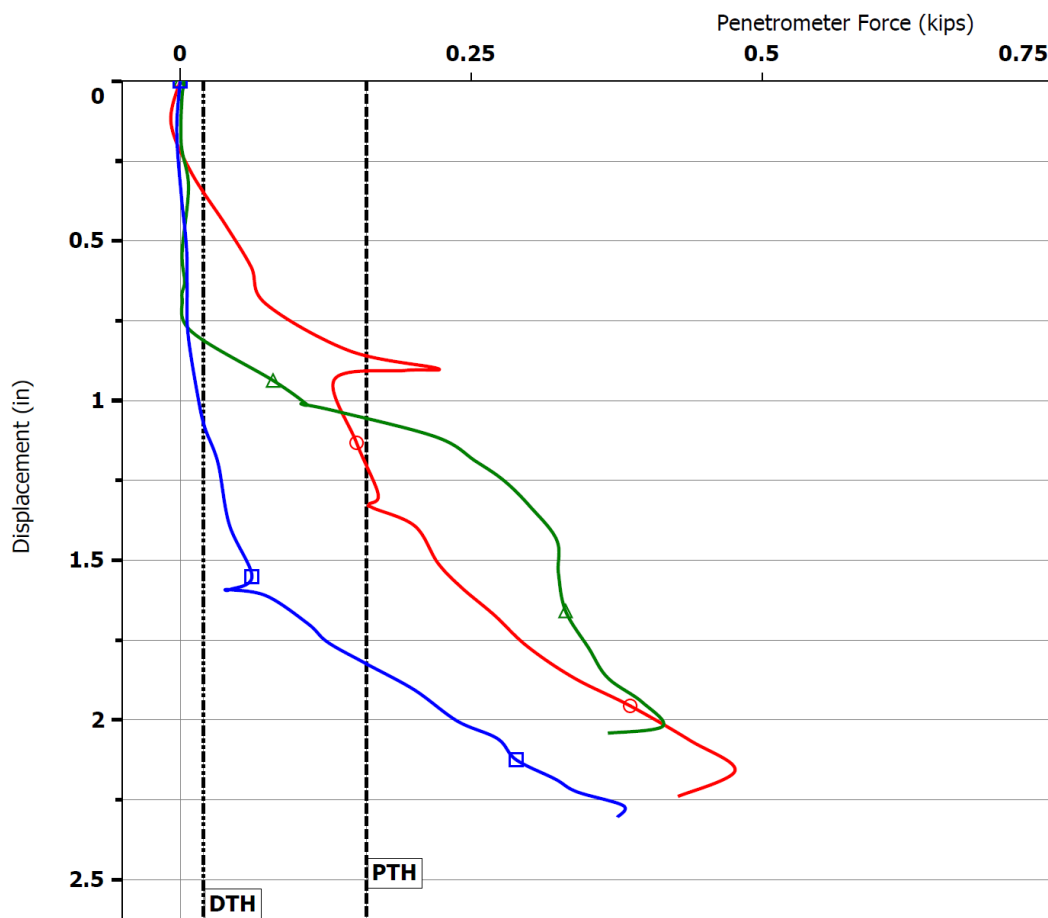
Test Table

Flat Tip penetrometers	30016DC	30022DC	30015DC
Disp. at 0.160 kips (in)	0.85	1.06	1.82
Disp. at 0.020 kips (in)	0.34	0.81	1.06
Debris thickness (in)	0.51	0.25	0.76



Collected Time: 9/23/2019 1:25:31 PM

30016DC 30022DC 30015DC



SQUID-S Version 0.9.4.1
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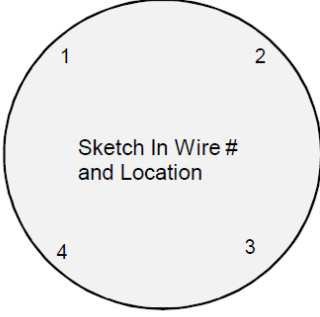


Figure 72. Graph. SQUID results for test drilled shaft #1 (run number 2).

INSTALLATION RECORDS

Figure 73 shows a sketch of the TIP wires configuration with wire-wire distances at the bottom of the cage, the serial number for each wire, and general drilled shaft information.





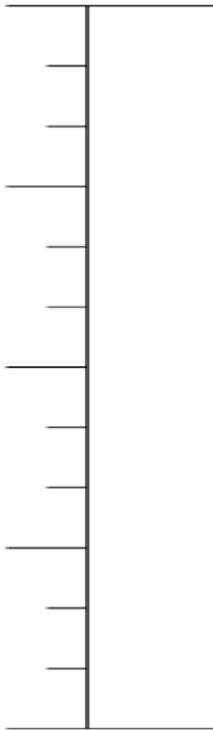
Sketch In Wire #
and Location

Wire #	Serial #	Wire Length (#nodes)	Nodes Above Concrete	Wire Tested After Install
1	43764	55		yes
2	43759	55		yes
3	43758	55		yes
4	43765	55		yes

Designate Northerly wire as #1

Wire-Wire Distance		
1-3 <u>40</u> in.	2-3 <u>29</u> in.	4-3 <u>28.75</u> in.
2-1 <u>28</u> in.	4-1 <u>27.5</u> in.	

Elevation 688.51 ft



Shaft Information		
	Design	As-Built
Shaft Dia.	48 in.	_____ in.
Shaft Length	50 ft.	_____ ft.
Concrete Vol.	26.2 cy.	_____ cy.
Cage Length	53 ft.	_____ ft.
Cage Dia.	42 in.	_____ in.
Casing Dia. (perm./temp.)	-/54 in.	_____ in.
Casing Length	8.5 ft.	_____ ft.
Rock Socket Dia.	- in.	- in.
Rock Socket Length	- ft.	- ft.

Field Notes:

Start of Placement - _____

End of Placement - _____

Placement Method - _____

Legend			
TOC	Top of Casing	BOC	Bottom of Casing
TOG	Top of Ground	BORC	Bottom of Reinf. Cage
TOS	Top of Shaft	BOS	Bottom of Shaft
TORS	Top of Rock Socket	▼	Water Level

* indicate changes in diameter

Figure 73. Illustration. TIP installation log for test drilled shaft #1.

Figure 74 shows a diagram of the typical access tube configuration including the CSL tube numbers and the CSL testing combination, temporary casing and drilled shaft diameter and the location of the reinforcement cage. Figure 75 through Figure 79 show the excavation logs for test drilled shaft #1.

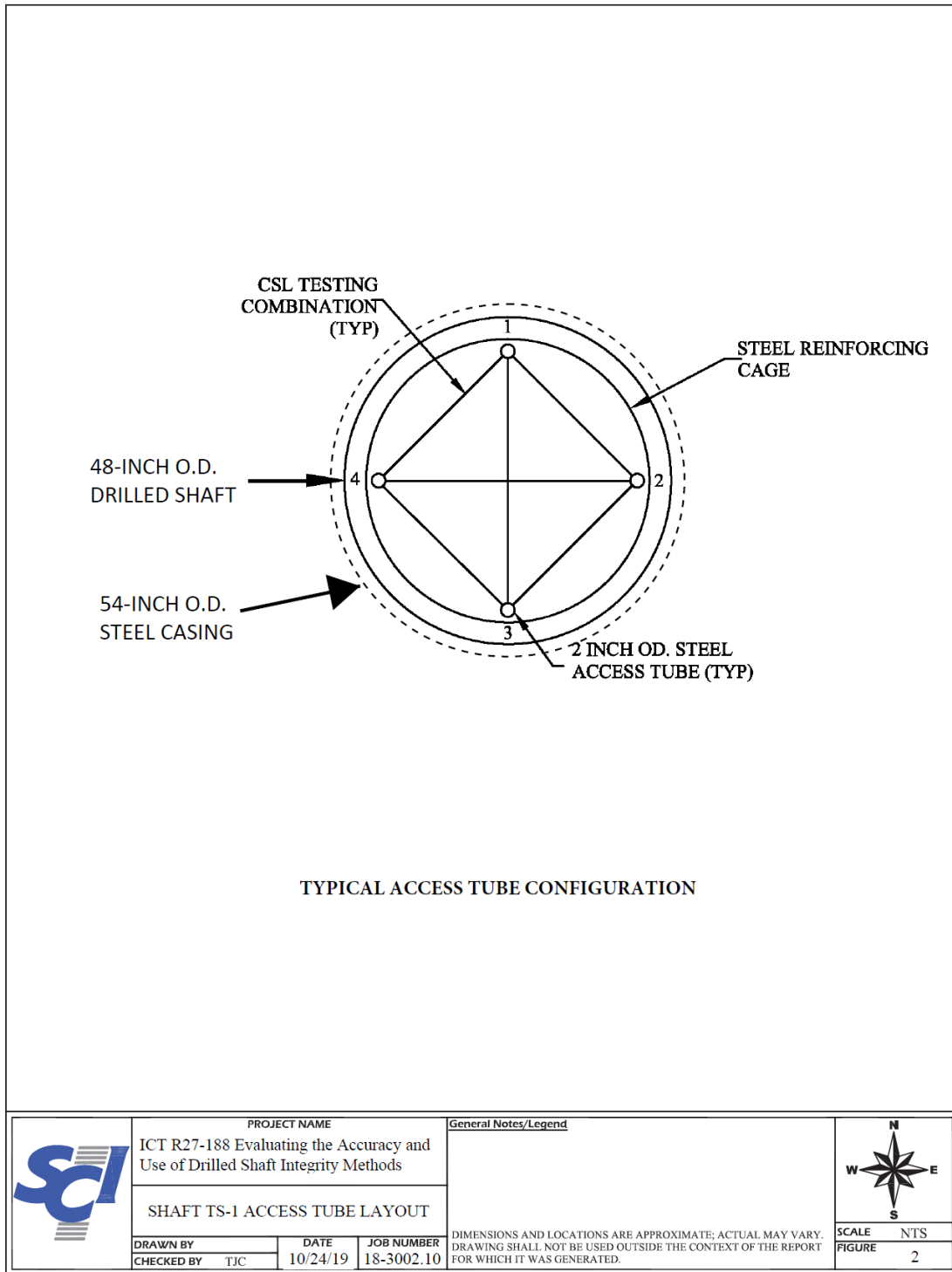


Figure 74. Illustration. Consultant B’s CSL access tube configuration for test drilled shaft #1.

Project Name:	IDOT Test Shaft in Decatur, IL	Page	1	of	7
SCI Project No.:	R27-188	Shaft Group:			
Contractor:	Illini Drilled Foundations	Shaft Number:	1		
Inspectors:	Tim Stark and Haode Wang - UIUC	Date:	9/23/2019		
SCI Reviewer:	Tom Casey				

Casing Information					Drilling Information
ID	OD	TOC Elev.	Length	BOC Elev.	
54"		690.01'	8.5'	681.51'	Soil Auger Dia. (ft):
					Rock Core Dia. (ft):
					Gnd Surface Elev. (ft): 688.51
					Water Table Elev. (ft): n/a
					Reference Elev. (ft): 688.51
					Drilling Mud:
Notes: Casing length of 8.5' (7' below ground surface, 1.5' above)					

Depth (ft)	Elevation (ft)	Time		Soil Description and Notes
0	688.51	802	In	Hard brownish grey clay
1.5	687.01	803	Out	
1.5	687.01	803	In	Hard light grey clay
2.2	686.31	805	Out	
2.2	686.31	805	In	Medium grey clay
2.81	685.7	807	Out	
2.81	685.7	808	In	Medium brown clay
3.03	685.48	809	Out	
3.03	685.48	810	In	Hard grey sandy clay
3.83	684.68	811	Out	
3.83	684.68	811	In	Medium brownish grey clay
4.47	684.04	812	Out	
4.47	684.04	813	In	Medium brownish grey clay
5.26	683.25	814	Out	
5.26	683.25	814	In	Hard brownish grey clay
5.98	682.53	815	Out	
5.98	682.53	816	In	Hard brownish grey clay
6.64	681.87	817	Out	
6.64	681.87	817	In	Hard light grey brownish sandy clay
7.40	681.11	818	Out	

Figure 75. Table. Excavation log #1 for test drilled shaft #1.

Project Name:	IDOT Test Shaft in Decatur, IL	Page	2	of	7
SCI Project No.:	R27-188	Shaft Group:			
Contractor:	Illini Drilled Foundations	Shaft Number:	1		
Inspectors:	Tim Stark and Haode Wang - UIUC	Date:	9/23/2019		
SCI Reviewer:	Tom Casey				

Casing Information					Drilling Information
ID	OD	TOC Elev.	Length	BOC Elev.	
54"		690.01'	8.5'	681.51'	Soil Auger Dia. (ft):
					Rock Core Dia. (ft):
					Gnd Surface Elev. (ft): 688.51
48"	No casing (shaft)	681.51'	43'	638.51'	Water Table Elev. (ft): n/a
					Reference Elev. (ft): 688.51
					Drilling Mud:
Notes: Casing length of 8.5' (7' below ground surface, 1.5' above)					

Depth (ft)	Elevation (ft)	Time		Soil Description and Notes
7.4	681.11	818	In	Hard brownish grey clay
7.57	680.94	819	Out	
7.57	680.94	820	In	Medium brownish grey clay
9.17	679.34	821	Out	
9.17	679.34	821	In	Medium grey clay
10.12	678.39	822	Out	
10.12	678.39	823	In	Medium grey clay
11.3	677.21	824	Out	
11.3	677.21	825	In	Medium brownish grey clay
12.14	676.37	826	Out	
12.14	676.37	826	In	Medium brownish grey sandy clay
13.36	675.15	827	Out	
13.36	675.15	828	In	Medium grey sandy clay
14.59	673.92	829	Out	
14.59	673.92	829	In	Moist medium grey clay
15.88	672.63	830	Out	
15.88	672.63	831	In	Hard dark grey clay
17.4	671.11	832	Out	
17.4	671.11	832	In	Medium grey clay
18.4	670.11	833	Out	

Figure 76. Table. Excavation log #2 for test drilled shaft #1.

Project Name:	IDOT Test Shaft in Decatur, IL	Page	3	of	7
SCI Project No.:	R27-188	Shaft Group:			
Contractor:	Illini Drilled Foundations	Shaft Number:	1		
Inspectors:	Tim Stark and Haode Wang - UIUC	Date:	9/23/2019		
SCI Reviewer:	Tom Casey				

Casing Information					Drilling Information
ID	OD	TOC Elev.	Length	BOC Elev.	
54"		690.01'	8.5'	681.51'	Soil Auger Dia. (ft):
					Rock Core Dia. (ft):
					Gnd Surface Elev. (ft): 688.51
48"	No casing (shaft)	681.51'	43'	638.51'	Water Table Elev. (ft): n/a
					Reference Elev. (ft): 688.51
					Drilling Mud:
Notes: Casing length of 8.5' (7' below ground surface, 1.5' above)					

Depth (ft)	Elevation (ft)	Time		Soil Description and Notes
18.4	670.11	833	In	Hard grey sandy clay
19.48	699.03	834	Out	
19.48	699.03	834	In	
20.85	667.66	835	Out	Hard grey sandy clay
20.85	667.66	836	In	
22.03	666.48	837	Out	Medium brownish grey clay
22.03	666.48	838	In	
23.34	665.17	839	Out	Medium brownish grey clay with sand grains
23.34	665.17	839	In	
25.01	663.5	840	Out	Moist brownish grey sandy clay
25.01	663.5	840	In	
26.23	662.28	841	Out	Soft - Medium dark grey sandy clay
26.23	662.28	940	In	
27.39	661.12	943	Out	Medium dark grey clay
27.39	661.12	944	In	
28.73	659.78	946	Out	Medium brownish grey clay
28.73	659.78	947	In	
30.53	657.98	950	Out	Soft moist greyish brown clay
30.53	657.98	952	In	
32.52	655.99	955	Out	Soft moist light brown clay

Figure 77. Table. Excavation log #3 for test drilled shaft #1.

Project Name:	IDOT Test Shaft in Decatur, IL	Page	4	of	7
SCI Project No.:	R27-188	Shaft Group:			
Contractor:	Illini Drilled Foundations	Shaft Number:	1		
Inspectors:	Tim Stark and Haode Wang - UIUC	Date:	9/23/2019		
SCI Reviewer:	Tom Casey				

Casing Information					Drilling Information
ID	OD	TOC Elev.	Length	BOC Elev.	
54"		690.01'	8.5'	681.51'	Soil Auger Dia. (ft):
					Rock Core Dia. (ft):
					Gnd Surface Elev. (ft): 688.51
	No casing (shaft)	681.51'	43'	638.51'	Water Table Elev. (ft): n/a
48"					Reference Elev. (ft): 688.51
					Drilling Mud:

Notes: Casing length of 8.5' (7' below ground surface, 1.5' above)

Depth (ft)	Elevation (ft)	Time		Soil Description and Notes
32.52	655.99	1000	In	Soft moist light brown clay
35.07	653.44	1002	Out	
35.07	653.44	1002	In	Wet soft brownish grey clay
36.87	651.64	1004	Out	
36.87	651.64	1005	In	Wet soft brownish grey clay
38.65	649.86	1007	Out	
38.65	649.86	1008	In	Wet soft brownish grey clay
40.02	648.49	1010	Out	
40.02	648.49	1015	In	Wet medium brownish grey clay
41.34	647.17	1017	Out	
41.34	647.17	1018	In	Wet medium grey clay
42.9	645.61	1020	Out	
42.9	645.61	1020	In	Soft greyish brown clay
44.91	643.6	1022	Out	
44.91	643.6	1024	In	Soft greyish brown clay
47.09	641.42	1026	Out	
47.09	641.42	1030	In	Medium grey brownish clay
48.7	639.81	1032	Out	
			In	
			Out	

Figure 78. Table. Excavation log #4 for test drilled shaft #1.

Project Name:	IDOT Test Shaft in Decatur, IL	Page	5	of	7
SCI Project No.:	R27-188	Shaft Group:			
Contractor:	Illini Drilled Foundations	Shaft Number:	1		
Inspectors:	Tim Stark and Haode Wang - UIUC	Date:	9/23/2019		
SCI Reviewer:	Tom Casey				

Type of Drilling Fluid	Dry	Reinforcing Cage	
Bottom Cleanout Method		Shaft Plumbness Check/4ft	
Time/Date Final Cleanout		Proper # Vertical Bars	
Top of Rock Elevation (ft)		Proper # Horizontal Bars	
Bottom of Rock Elevation (ft)		Side Spacers	yes
Rock Socket Dia. (in)		Bottom Spacers	
Shaft Bottom Elev. (ft)	638.51	Ties and Connections	yes
Est. Shaft Bottom Dia. (ft)	4		

Inspector	Type	Time			
			Start (Prior to Steel Placement)		Test prior to Steel Placement
			Finish (Prior to Steel Placement)		
			Start (Prior to Concrete Placement)		Test prior to Concrete Placement
			Finish (Prior to Concrete Placement)		

Type:

V - Visual

S - Sounding

MS - Mini-SID

N

W

E

NOTES	S	Comments/Recommendations

Results:	☐ Satisfactory ☐ Unsatisfactory	DS Foreman _____ SCI Inspector _____	Date/Time _____
----------	--	---	-----------------

Figure 79. Illustration. Excavation log #5 for test drilled shaft #1.

DRILLED SHAFT CONCRETE PLACEMENT LOG									
Project Name:		IDOT Test Shaft in Decatur, IL				Page		6 of 7	
SCI Project No.:		R27-188				Shaft Group:			
Contractor:		Illini Drilled Foundations				Shaft Number:		1	
Inspectors:		Tim Stark and Haode Wang - UIUC				Date:		9/23/2019	
Placement Method		X Tremie		Volume in Pump Truck		#		ID	
		Pumped		Pump Truck Lines				5"	
				Pump Truck Hopper				Vol. 1/4 yd ³	
Ref. Elev.		688.51'							
TOC Elev.		690.01'							
TOS Elev.		691.51'		Total Volume in Lines + Pump Truck				Σ = 3/4 yd ³	
TOR Elev.									
BOC Elev.		681.51'		Time First Truck Batched:		1512			
BOR Elev.				Depth of Water per Hour Inside Shaft (Dry Hole Check):					
BOS Elev.		638.51'		Rebar Cage Top Elev (Start):				(Finish):	
Truck No.	Concrete Volume	Arrival Time	Start Time	Finish Time	Tremie Depth	Depth to Concrete	Notes		
1	6	1512	1524	1530	-47"	-35.2'			
2	6	1530	1536	1544	-43.3'	-28.2'			
3	9	1745	1800	1813	-29'	-12.8'			
4	9	1814	1823	1830	-28.5'	+0.5'			
Temp Casing Removal		OD	Top Elev.	Bot. Elev.	Start	Finish	Rebar Cage		
		54"	690.01'	688.51'	1900	1910	Centered:		
							Re-Centered:		
Notes:									

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Project Name:		IDOT Test Shaft in Decatur, IL		Page		7		of		7	
SCI Project No.:		R27-188		Shaft Group:							
Contractor:		Illini Drilled Foundations		Shaft Number:		1					
Inspectors:		Tim Stark and Haode Wang - UIUC		Date:		9/23/2019					

Date Cased		9/23/2019				Const.		Temp.	
Date Opened		9/23/2019		Casing Type				X	
Date Concrete Placed		9/23/2019		Casing Outside Diameter (OD) (ft)				54"	
				Bot. Of Casing (BOC) Elev. (ft)				681.51'	
Elev. (ft)		Depth (ft)		Top Of Casing (TOC) Elev. (ft)				690.01'	
				Dia. of Rock Socket (ft)				-	
688.51'		0		Shaft Diameter (ft)				4	
				Ground Surface Elevation (ft)				688.51'	
				Wet & Dry Shaft Length (ft)				50'	
				Rock Socket Length (ft)				-	
				Top Of Shaft (TOS) Elevation (ft)				691.51'	
				Bot. Of Shaft (BOS) Elevation (ft)				638.51'	
				Constructed Shaft Length (ft)				50'	
				Reinforcing Steel Cage Placed				yes	

Volume of Concrete			
Design Mix			
Theoretical (VTh)	23.2 yd³	Actual (VP)	30 yd³
OP (VP-VTh)		UP (VTh - VP)	
Duration (min)			

Legend:			
TOC	Top Of Casing		Sand
TOG	Top Of Ground		
TOS	Top Of Shaft		Silt
TOR	Top Of Rock		
BOC	Bottom Of Casing		Clay
BOS	Bottom Of Shaft		
BOR	Bottom Of Rock		Rock

Contractor: Illini Drilled Foundations	
Notes:	

Elev. (ft)	Depth (ft)	
688.51'	0	
681.51'	7	
638.51'	50	

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APPENDIX D: TEST DRILLED SHAFT #2

SITE INVESTIGATION

Test drilled shaft #2 is located 0.5 miles north of Sherrill Road along IL-47 in Kendall County, Illinois as shown in Figure 82.



Figure 82. Photo. Location of test drilled shaft #2, 0.5 miles north of Sherrill Road along IL-47 in Kendall County, Illinois.

Two soil borings were conducted using a hollow stem auger and a split spoon sampler on February 21, 2020 and on March 13, 2020 as shown in Figure 83 and Figure 84, respectively. Figure 85 shows the plan view of test drilled shaft #2 site location. The ground surface elevation is 592.6 ft. the second soil boring (see Figure 84) shows that the blow count every twelve inches (N-value) is 2 before reaching the eroded rock layer at a depth of 7.5 ft. The unconfined compression strength and the moisture content range between 0.5 tsf to 0.8 tsf and between 24% to 33%, respectively before reaching the eroded rock layer at a depth of 7.5 ft.

In the first soil boring (see Figure 83) The soil encountered is stiff brown silty clay to clay loam from the ground surface to depth of 7 ft. However, a weathered and fractured limestone layer was encountered at depth of 7 ft and therefore the boring ended. In the second soil boring (see Figure 84) the soil encountered is augured black silty clay loam fill from the ground surface to depth of 2.5 ft. However, a weathered and fractured limestone layer was encountered at depth of 7 ft and therefore

the boring ended. Silty layers consist of medium black, brown, grey silty clay with sand were encountered from depth of 2.5 ft to 7.5 ft, and another 1.5 ft of dense angular limestone gravel was encountered from depth of 7.5 ft to 9 ft. The limestone was encountered at depth of 9 ft after which the boring ended due to auger refusal.

The first encounter of the ground water during the first soil boring (see Figure 83) was at elevation of 591.1 ft (depth of 1.5 ft). The water level didn't change upon completion of soil boring. For the second soil boring (see Figure 84), the depth of the ground water was at depth of 3.5 ft and fell to depth of 4 ft upon completion of soil boring.

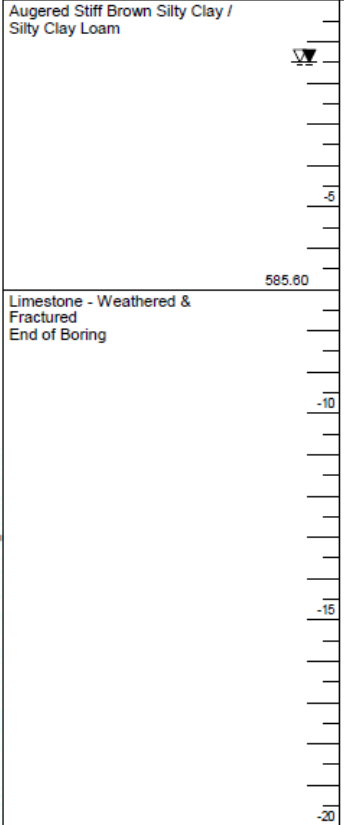
 Illinois Department of Transportation Division of Highways IDOT		SOIL BORING LOG		Page <u>1</u> of <u>1</u>	
ROUTE <u>IL 47</u>		DESCRIPTION <u>Drilled Shaft Test Site - IL 47, 0.5 miles North of Sherril Road in Kendall County</u>		Date <u>2/21/20</u>	
SECTION _____		LOCATION <u>NE 1/4, SEC. 33, TWP. 35N, RNG. 7E, 3rd PM,</u> Latitude <u>41.46652</u> , Longitude <u>-88.42356</u>			
COUNTY <u>Kendall</u>		DRILLING METHOD <u>Hollow Stem Auger</u>		HAMMER TYPE <u>CME Automatic</u>	
STRUCT. NO. _____ Station _____		DEPTH (ft) (6") (tsf) (%)	BULGE S Qu	MOIST T	Surface Water Elev. _____ ft Stream Bed Elev. _____ ft
BORING NO. <u>01</u> Station _____ Offset _____ Ground Surface Elev. <u>592.60</u> ft					Groundwater Elev.: First Encounter <u>591.1</u> ft Upon Completion <u>591.1</u> ft After _____ Hrs. _____ ft
Augered Stiff Brown Silty Clay / Silty Clay Loam 					
SOIL BORING DRILLED SHAFT TEST SITE - IL 47/GPJ IL DOT.GDT 3/19/20					
The Unconfined Compressive Strength (UCS) Failure Mode is indicated by (B-Bulge, S-Shear, P-Penetrometer) The SPT (N value) is the sum of the last two blow values in each sampling zone (AASHTO T206)					
BBS, form 137 (Rev. 8-99)					

Figure 83. Illustration. Soil Boring log #1 of test drilled shaft #2.

SOIL BORING LOG

Date 3/13/20

ROUTE	IL 47	DESCRIPTION	LOGGED BY
		Drilled Shaft Test Site - IL 47, 0.5 miles North of Sherril Road in Kendall County	Larry Myers

SECTION _____ LOCATION NE 1/4, SEC. 33, TWP. 35N, RNG. 7E, 3rd PM,

COUNTY	Kendall	DRILLING METHOD	Hollow Stem Auger	HAMMER TYPE	CME Automatic
--------	---------	-----------------	-------------------	-------------	---------------

STRUCT. NO. _____
Station _____

BORING NO. 02
Station _____
Offset _____
Ground Surface Elev. _____

D E P T H	B L O W S	U C S Qu	M O I S T
(ft)	(/6")	(tsf)	(%)

Surface Water Elev. _____ ft
Stream Bed Elev. _____ ft
Groundwater Elev.:
First Encounter _____ ft ▼
Upon Completion _____ ft ▼
After Hrs. _____ ft

[illegible]

The Unconfined Compressive Strength (UCS) Failure Mode is indicated by (B-Bulge, S-Shear, P-Penetrometer)
The SPT (N value) is the sum of the last two blow values in each sampling zone (AASHTO T206)

BBS, form 137 (Rev. 8-99)

Figure 84. Illustration. Soil Boring log #2 of test drilled shaft #2.

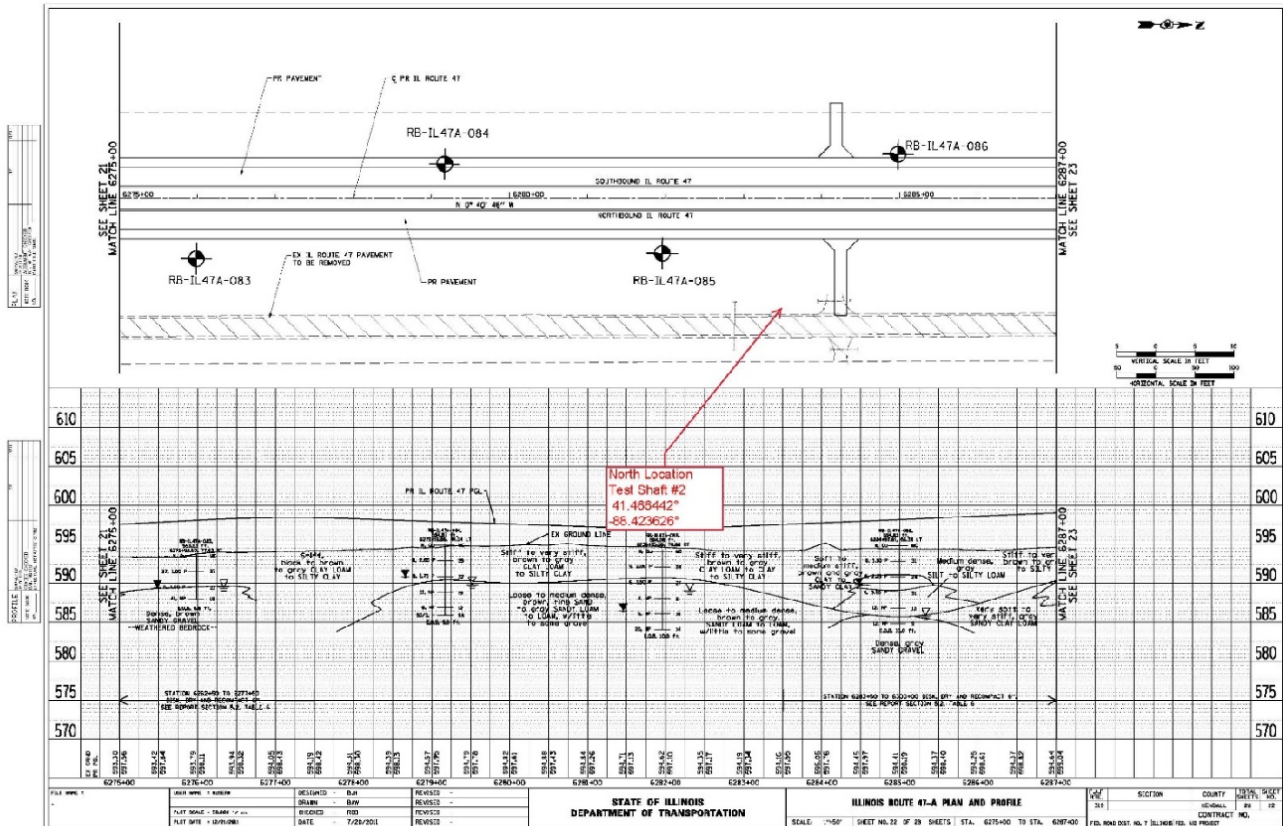


Figure 85. Illustration. Plan view of test drilled shaft #2 site location.

TEMPERATURE AT THE REBAR CAGE FOR AN IDEAL SHAFT

Figure 86 shows the 3D temperature profile model for drilled shafts after Johnson (2016) with black and red arrows added to show the temperature at the rebar cage for test drilled shaft #2. For this shaft, the diameter of the drilled shaft is 6 ft, the rebar cage diameter is 5.5 ft with a 2.75 ft radial position from the center of the drilled shaft. Applying the dimensions of test drilled shaft #2 as shown in Figure 86 leads to an expected peak temperature of 175 °F at the rebar cage.

Figure 87 shows the 2D temperature profile model after Mullins (1997) for drilled shafts with red arrows added to show the temperature at the rebar cage. The red line curve in Figure 87 is for a 6 ft diameter drilled shaft, and therefore, the red arrows inserted in this figure show that for a radial position of 2.75 ft (rebar cage diameter of 5.5 ft), the peak temperature should be 129 °F. Using the two different methods of estimating the concrete temperature provides a range of 129 °F to 175 °F, which is too large to be considered reliable.

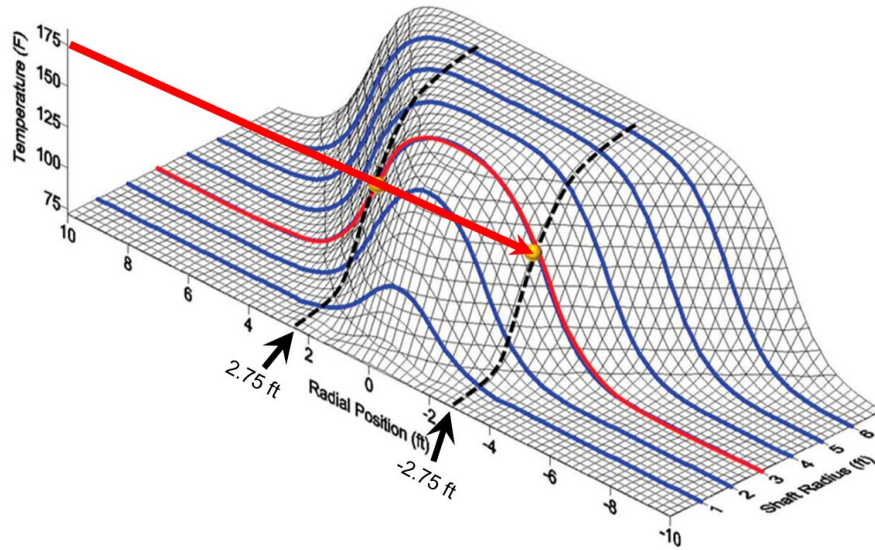


Figure 86. 3D graph. 3D temperature profile model for drilled shafts with black and red arrows added to show the temperature at the rebar cage of test shaft #2 (after Johnson, 2016).

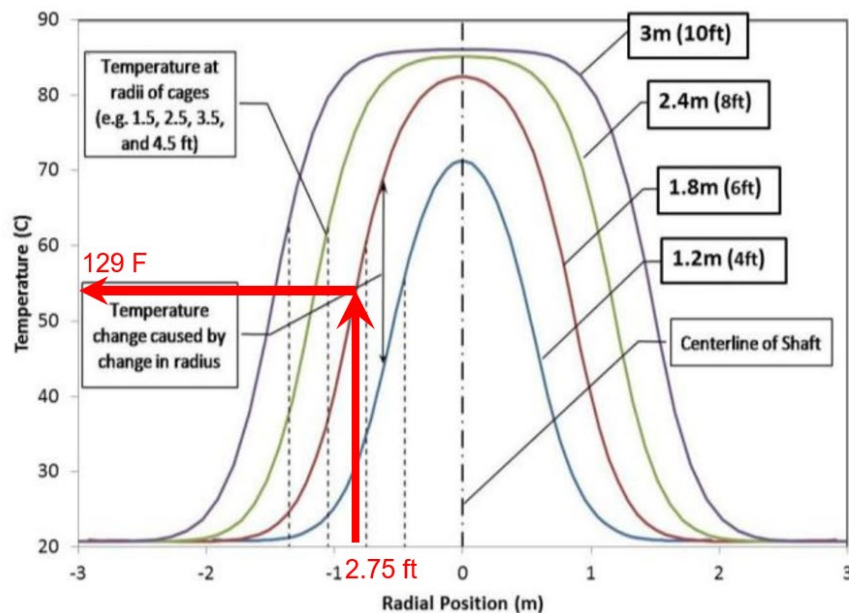


Figure 87. Graph. 2D temperature profile model for drilled shafts with red arrows added to show the temperature at the rebar cage of test shaft #2 (after Mullins, 1997).

CONSULTANT A'S TIP RESULTS

Consultant A's results for test drilled shaft #2 include the thermal integrity profile results that are presented in Figure 88(a) through Figure 90, Figure 92(a) through Figure 94, and Figure 96(a) through Figure 98 that show the measured temperatures (Fahrenheit degrees) vs. depth (ft) for the odd, even, and all wires, respectively. For the odd wires, the measured temperatures are shown at 6h 10m (see Figure 88(a)), 12h 2m (see Figure 88(b)), 18h 1m (see Figure 89(a)), 25h 29m (see Figure 89(b)), and

36h 6m (see Figure 90) after placement of concrete. Figure 91 (a) presents the estimated effective radius vs. depth for the odd wires, while a 3-D interpretation of the tested drilled shaft is presented in Figure 91 (b).



Figure 88. Graph. Temperature versus depth profile for the 6 odd wires in test drilled shaft #2: (a) at 6h 10m, and (b) at 12h 2m after concrete placement.

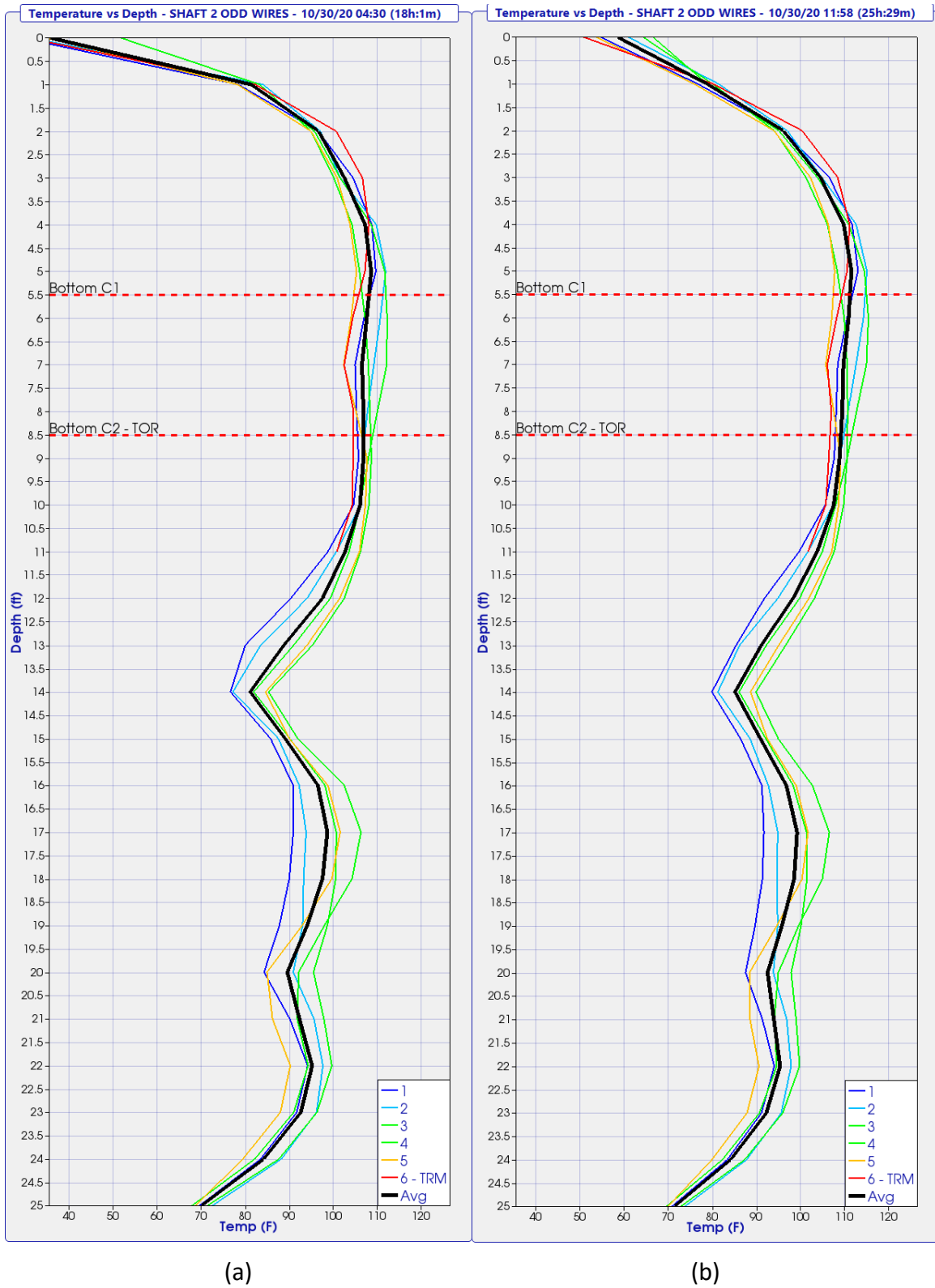


Figure 89. Graph. Temperature versus depth profile for the 6 odd wires in test drilled shaft #2: (a) at 18h 1m, and (b) at 25h 29m after concrete placement.

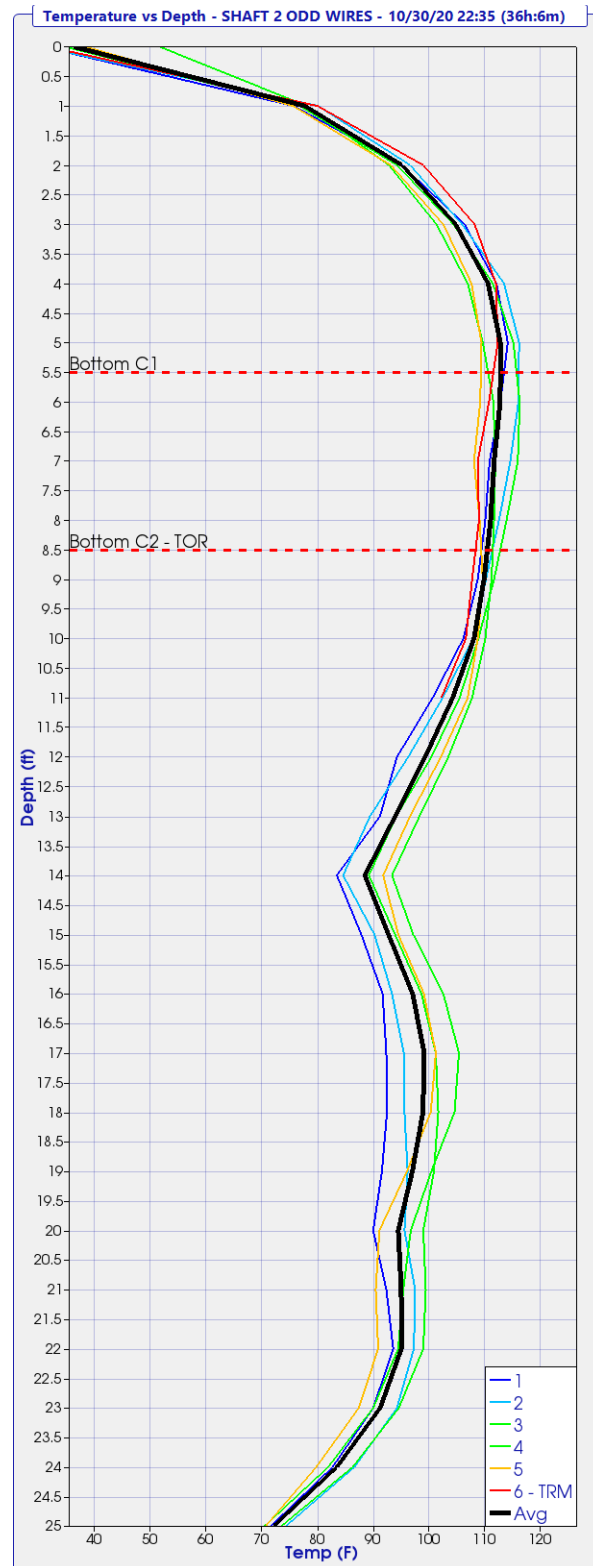


Figure 90. Graph. Peak temperature versus depth profile for the 6 odd wires in shaft #2 at 36h 6m.

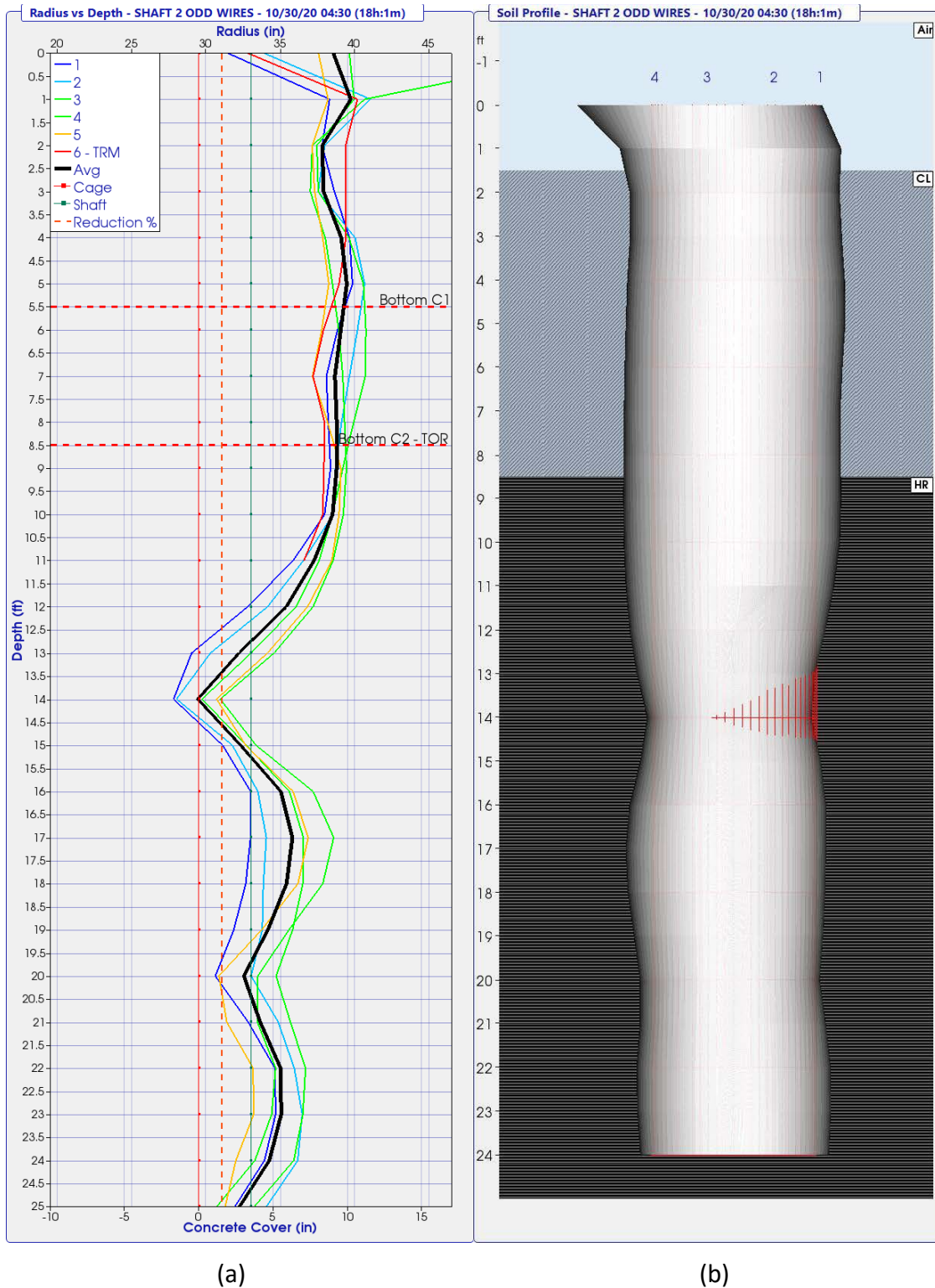


Figure 91. Graph. (a) radius versus depth and Illustration. (b) 3D rendering for the 6 odd wires in test drilled shaft #2.

For the even wires, the measured temperatures are shown at 6h 0m (see Figure 92(a)), 12h 6m (see Figure 92(b)), 18h 48m (see Figure 93(a)), 25h 36m (see Figure 93(b)), and 36h 26m (see Figure 94) after placement of concrete. Figure 95 (a) presents the estimated effective radius vs. depth for the even wires, while a 3-D interpretation of the tested drilled shaft is presented in Figure 95 (b).

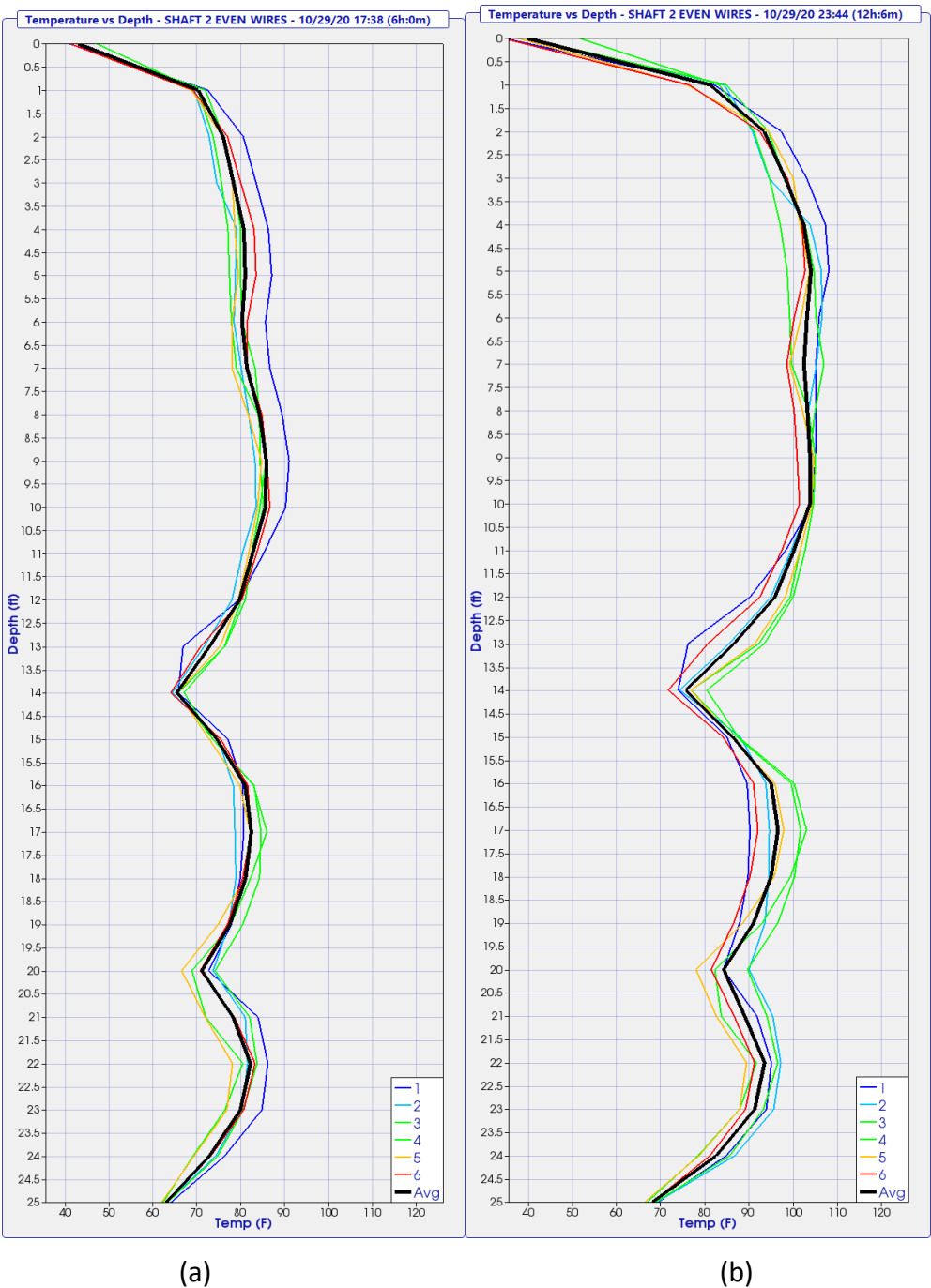


Figure 92. Graph. Temperature versus depth profile for the 6 even wires in test drilled shaft #2: (a) at 6h 0m, and (b) at 12h 6m after concrete placement.

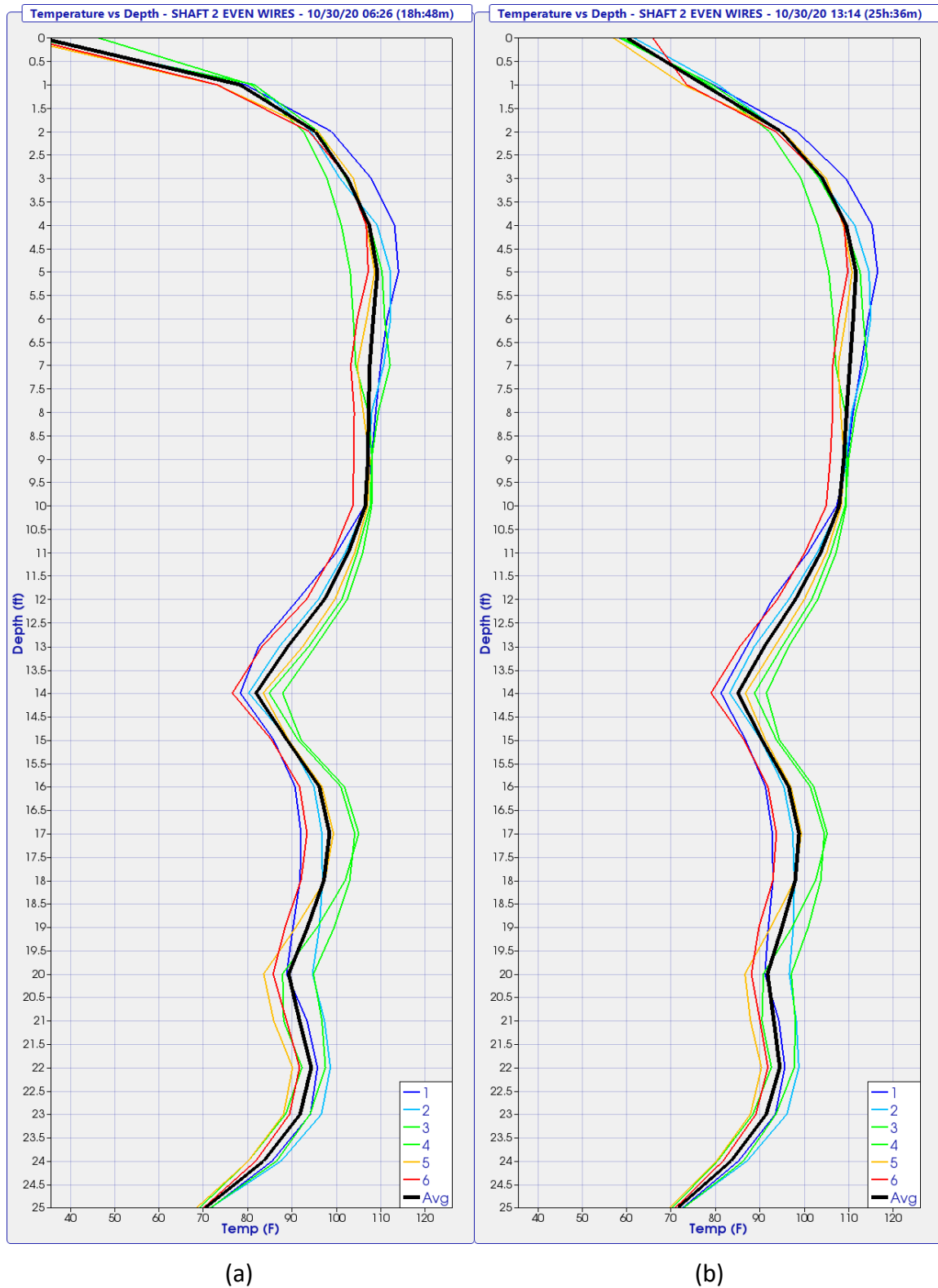


Figure 93. Graph. Temperature versus depth profile for the 6 even wires in test drilled shaft #2: (a) at 18h 48m, and (b) at 25h 36m after concrete placement.

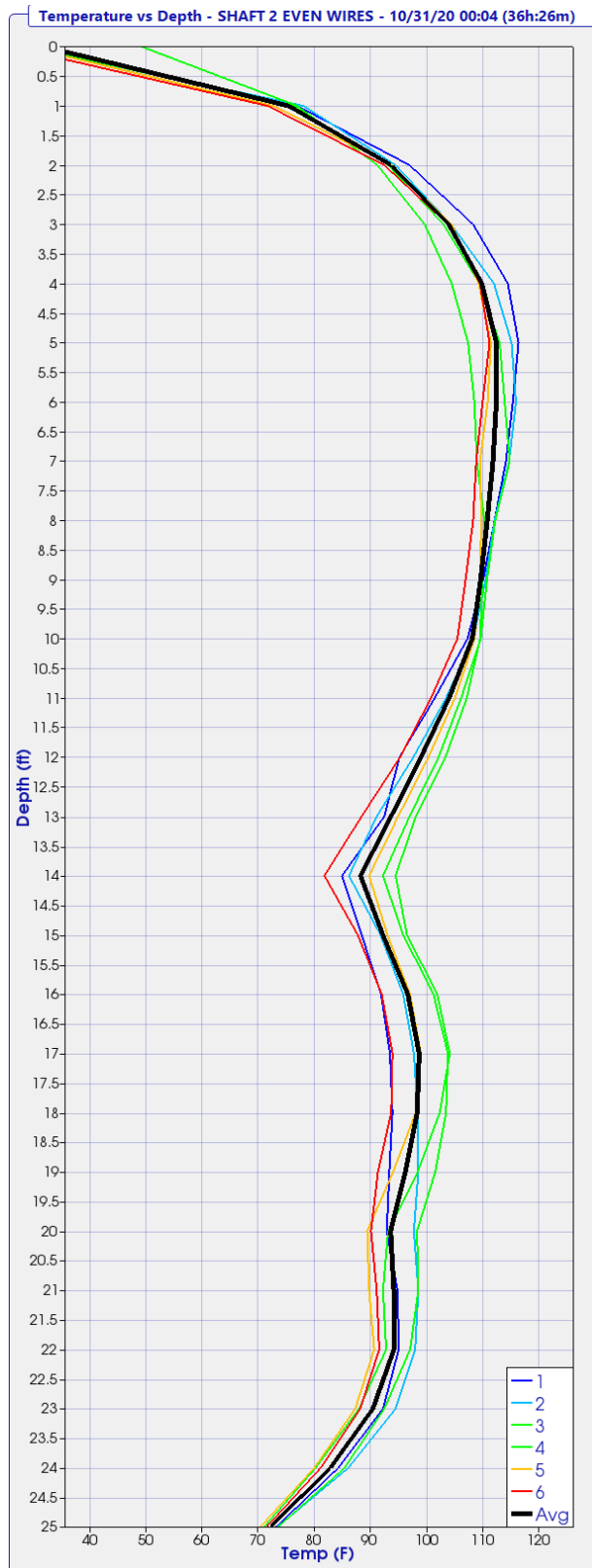


Figure 94. Graph. Peak temperature versus depth profile for the 6 even wires in test drilled shaft #2 at 36h 26m.

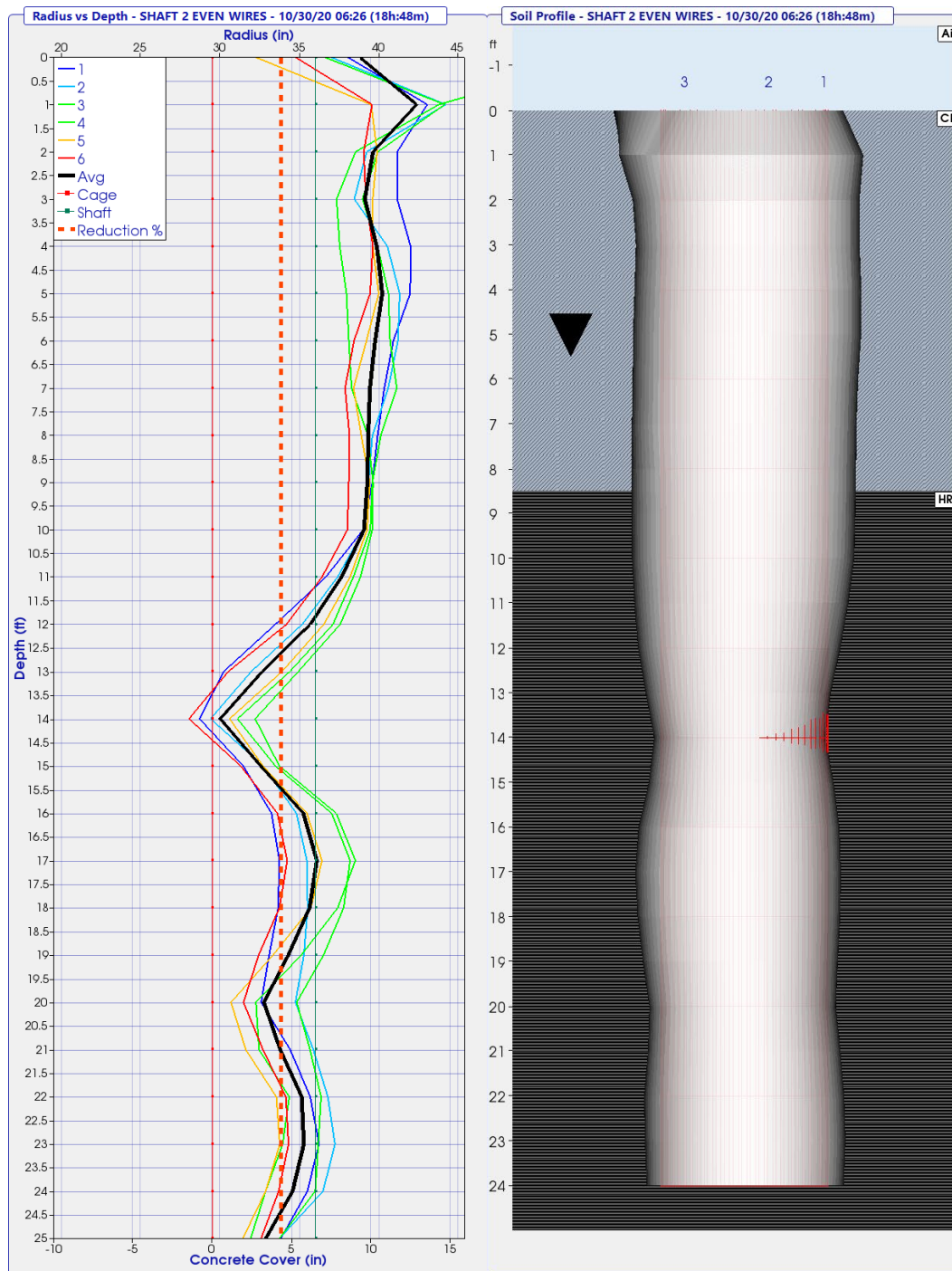
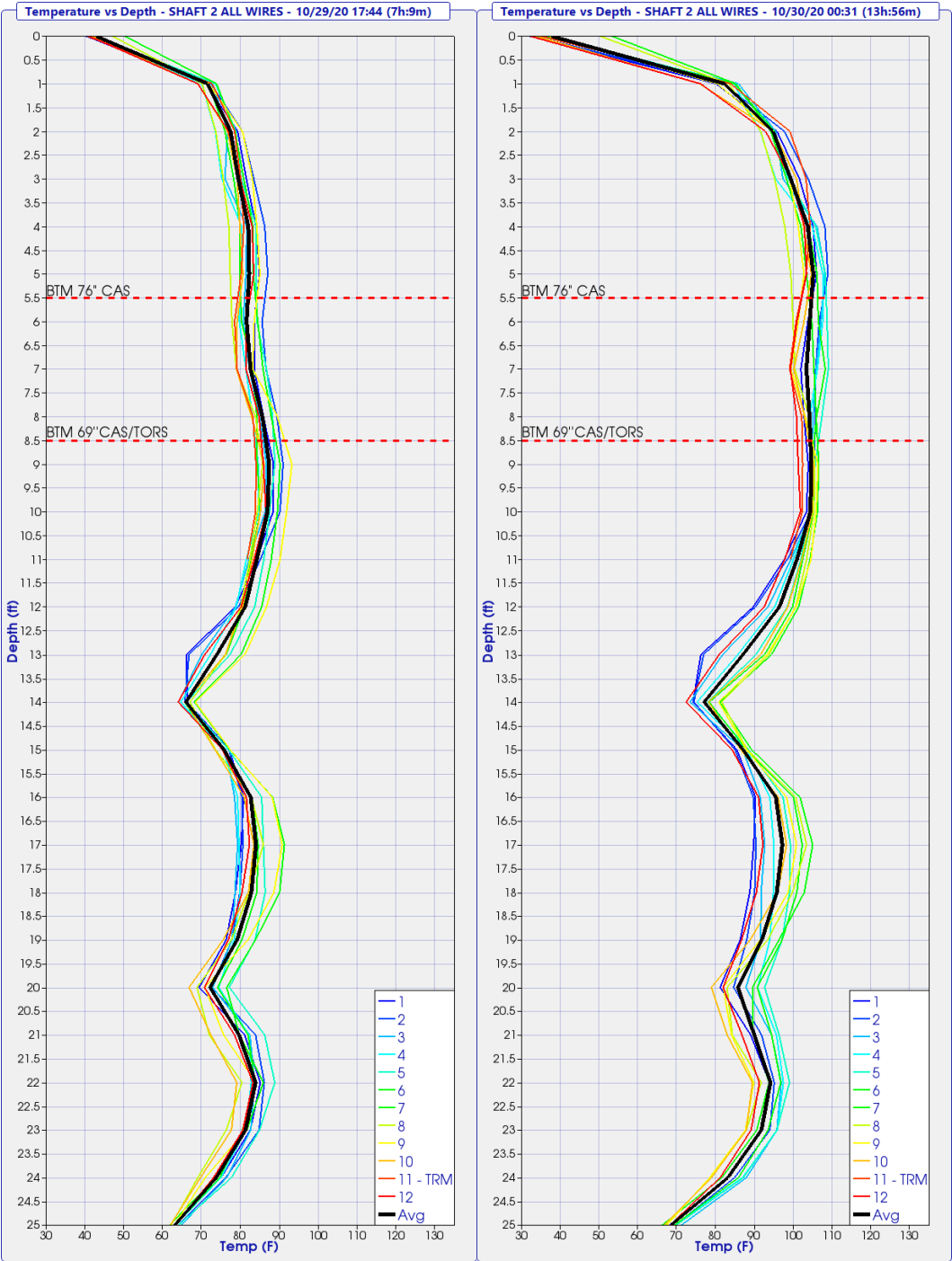


Figure 95. Graph. (a) radius versus depth and Illustration. (b) 3D rendering for the 6 even wires in test drilled shaft #2.

For all wires, the measured temperatures are shown at 7h 9m (see Figure 96(a)), 13h 56m (see Figure 96(b)), 18h 12m (see Figure 97(a)), 20h 27m (see Figure 97(b)), 29h 10m (see Figure 98 (a)), and 37h 17m (see Figure 98(b)), after placement of concrete. Figure 99 (a) presents the estimated effective

radius vs. depth for all the wires, while a 3D interpretation of the tested drilled shaft is presented in Figure 99 (b). The effective average radius is generally as expected relative to the reported casing diameters from the top of concrete to a depth of 10 ft.



(a)

(b)

Figure 96. Graph. Temperature versus depth profile for all the 12 wires in test drilled shaft #2: (a) at 7h 9m, and (b) at 13h 56m after concrete placement.

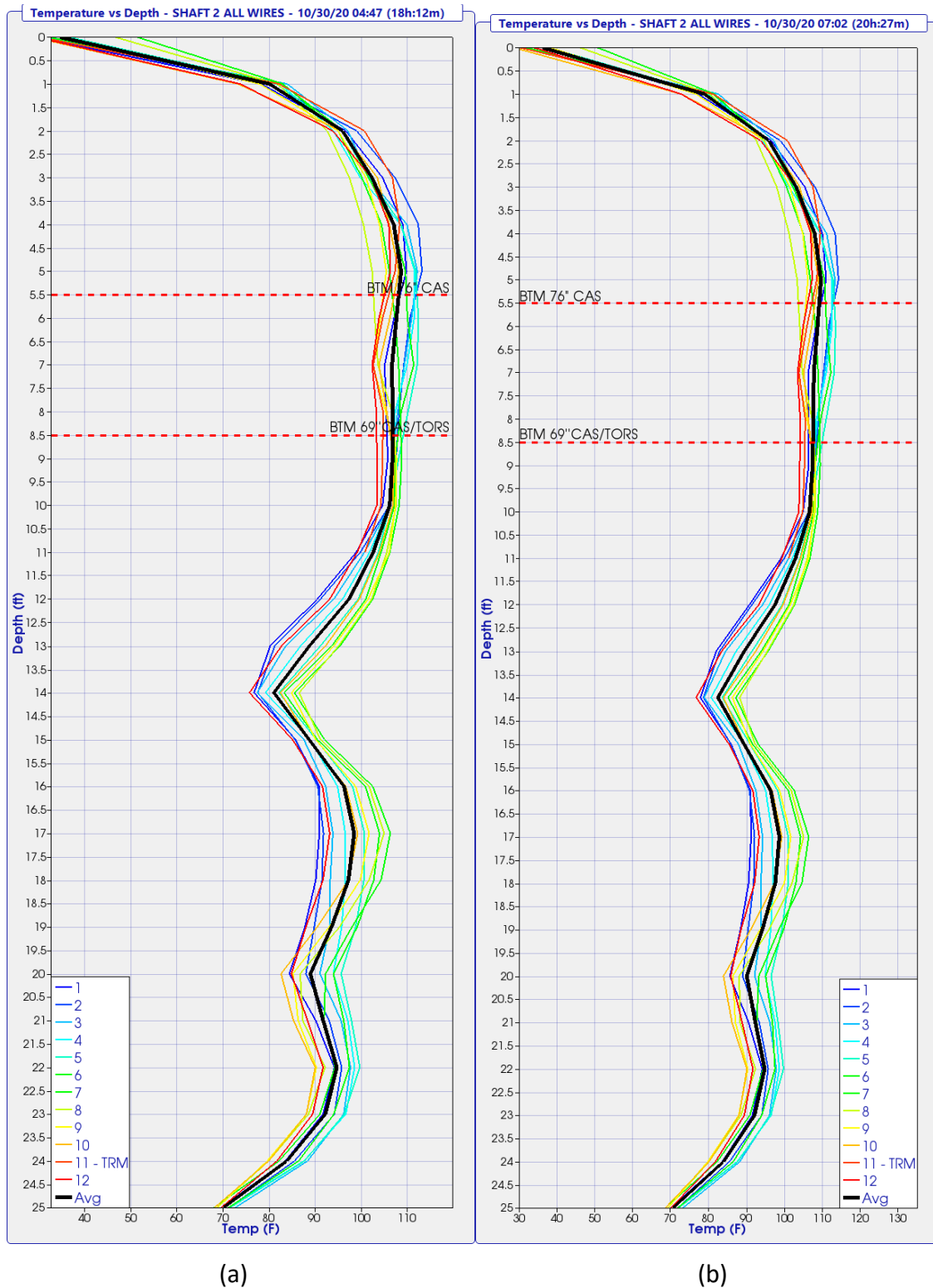


Figure 97. Graph. Temperature versus depth profile for all the 12 wires in test drilled shaft #2: (a) at 18h 12m, and (b) at 20h 27m after concrete placement.



Figure 98. Graph. Temperature versus depth profile for all the 12 wires in test drilled shaft #2: (a) at 29h 10m, and (b) at 37h 17m (peak) after concrete placement.

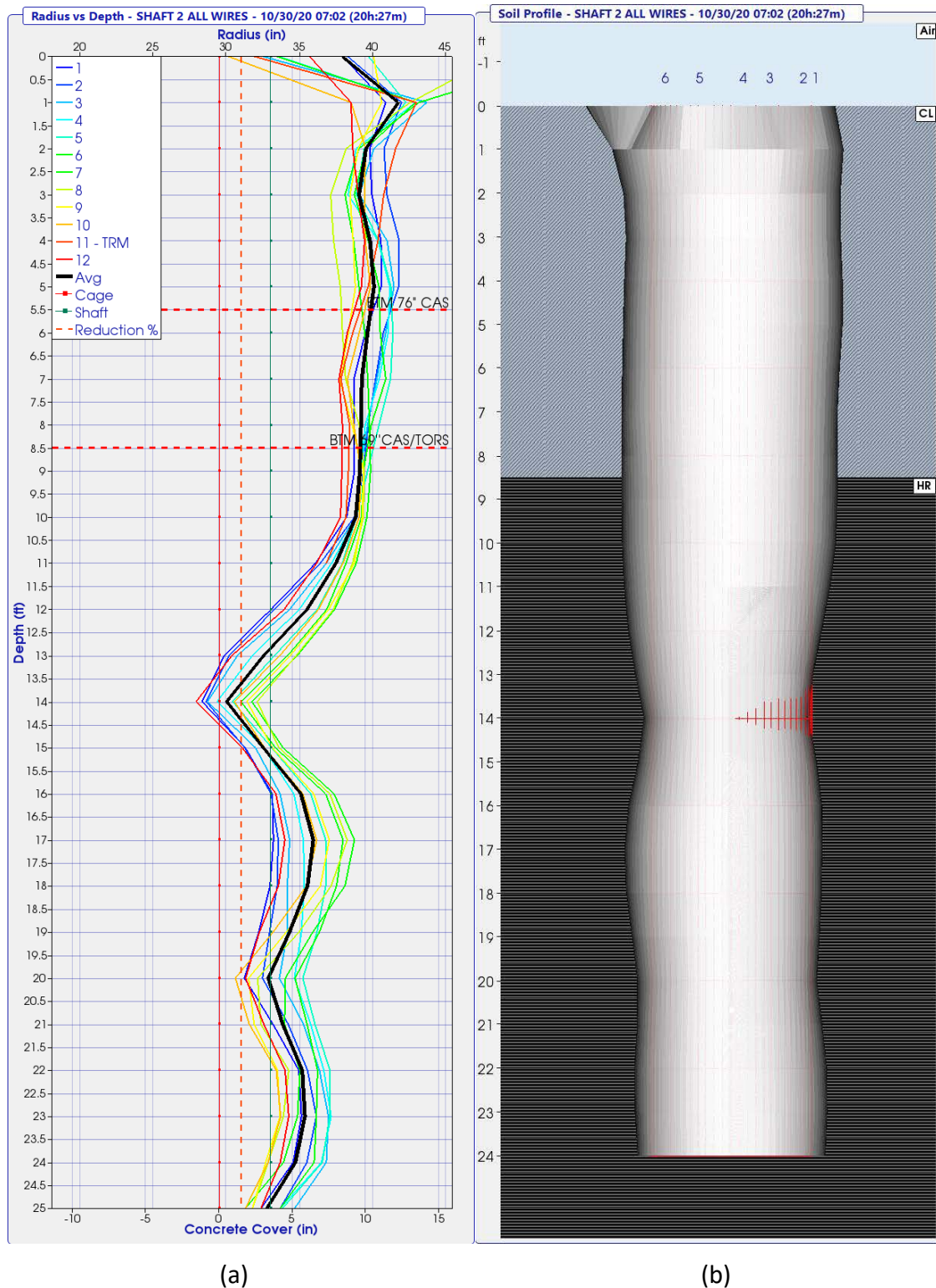


Figure 99. Graph. (a) radius versus depth and Illustration. (b) 3D rendering for all the 12 wires in test drilled shaft #2.

UIUC's Interpretation of TIP Results

Figure 100 shows the 3D rendering for test drilled shaft #2 with red arrows showing the defects' locations for the odd wires. Figure 101 shows the 3D rendering for test drilled shaft #2 with added arrows showing the defects' locations for the even wires. Figure 102 shows the 3D rendering for test drilled shaft #2 with added arrows showing the defects' locations for all the wires. The bold red dashed line in Figure 100, Figure 101, and Figure 102 shows the theoretical radius of the drilled shaft.

• Radius v. Depth

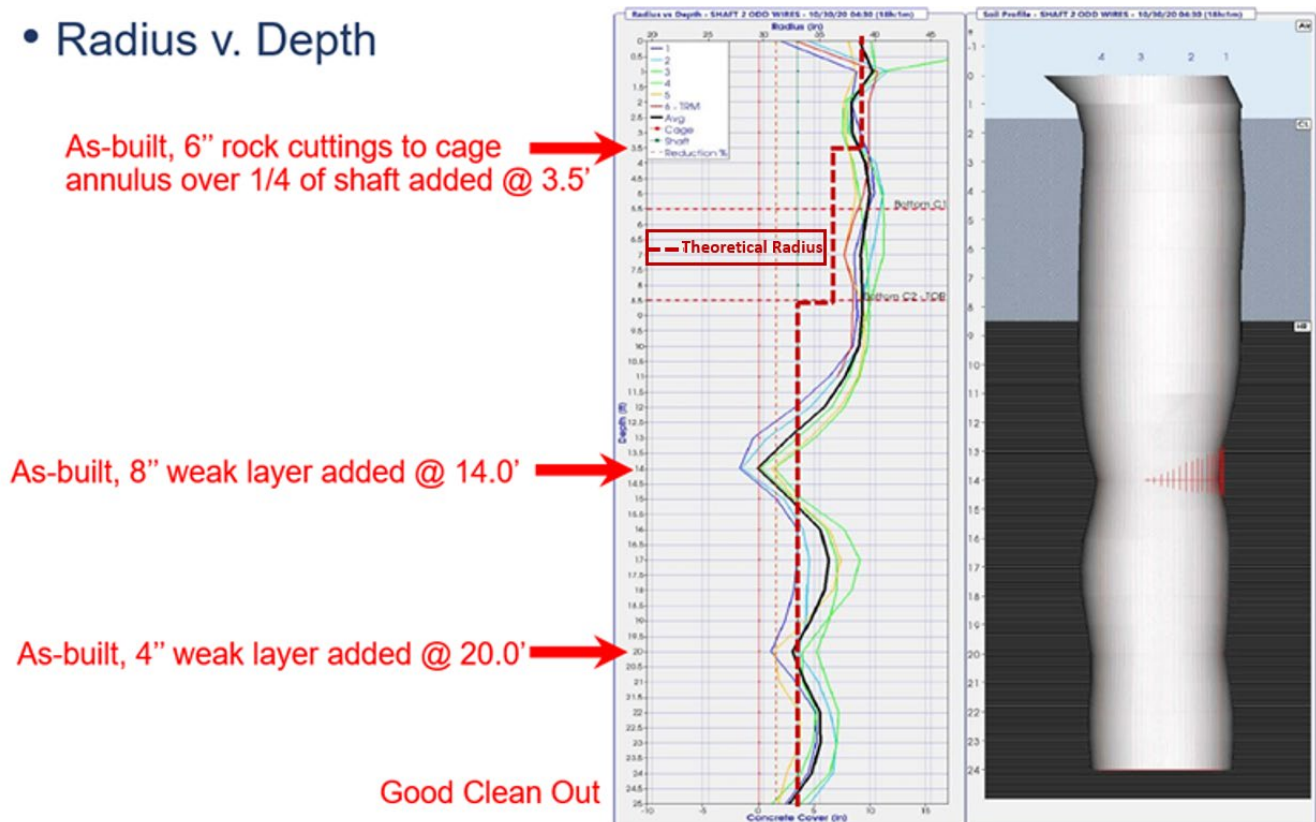


Figure 100. Illustration. 3D rendering for test drilled shaft #2 (odd wires).

- Radius v. Depth

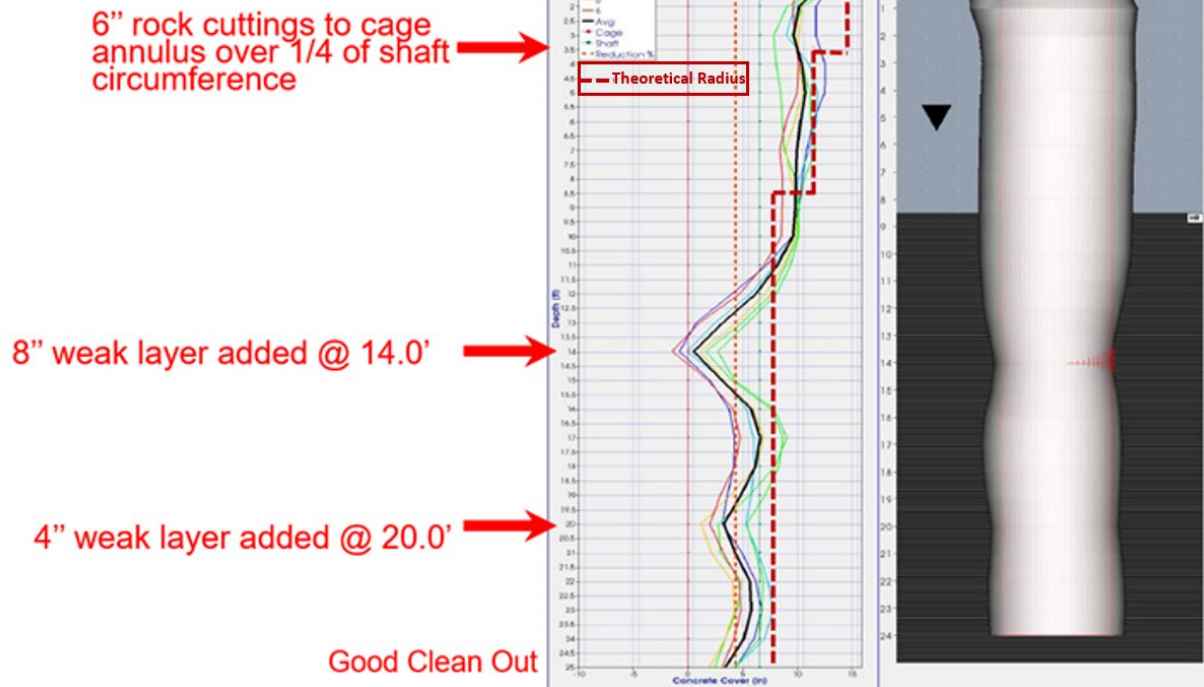


Figure 101. Illustration. 3D rendering for test drilled shaft #2 (even wires).

- Radius v. Depth

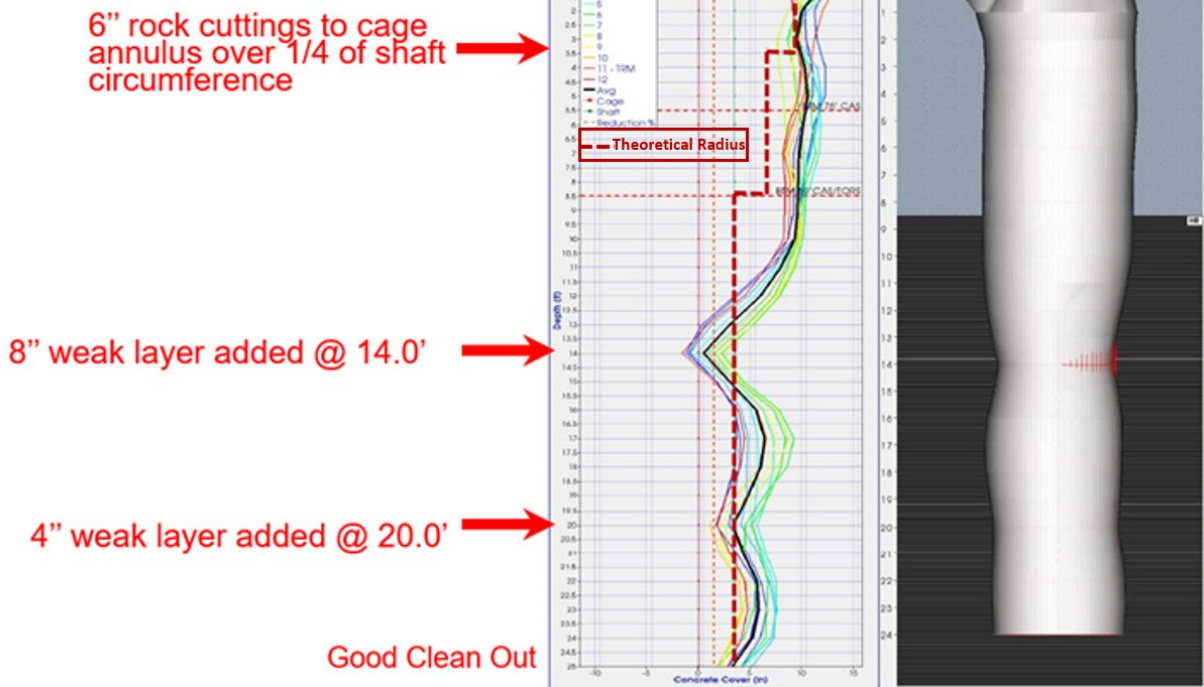


Figure 102. Illustration. 3D rendering for test drilled shaft #2 (all wires).

An interpretation of the measured temperature profiles with depth for all the thermal wires was also conducted by the research team. The temperatures profiles at the peak, and one-half the time to peak temperature are considered in the analysis described below. Boeckmann and Loehr (2018) show that the analysis of TIP data is more sensitive to defects at times corresponding to roughly one-half the time to peak temperature and yields more accurate assessment of potential defects. Figure 103 shows the temperature versus depth profile for the six odd thermal wires in test drilled shaft #2 at peak temperature and one-half the time to peak temperature. The temperature profiles shown in Figure 103(a) and Figure 103(b) are the same as those shown in Figure 89(a) and Figure 90, respectively. However, Figure 103 shows the defects locations. Figure 104 shows the temperature versus depth profile for the six even thermal wires in test drilled shaft #2 at peak temperature and one-half the time to peak temperature. The temperature profiles shown in Figure 104(a) and Figure 104(b) are the same as those shown in Figure 93(a) and Figure 94, respectively. However, the even wires in Figure 104 shows the defects locations. And similarly for the twelve thermal wires in test drilled shaft #2 in Figure 105 compared to Figure 97(a) and Figure 98(b). Figure 106 shows temperature profiles for test drilled shaft #2 one-half the time to peak temperature for the odd, even, and all wires. In Figure 103 through Figure 106, there are circles with colored numbers around them that shows the location of these wires. The boxes around the numbers indicates the location of the added cutting at the bottom of casing between the rebar cage and the casing over quarter of the annulus circumference at depth of 3.5 ft. The red circles without numbers in Figure 103 show the location at which wire # 6 has no data beyond a depth of 11 ft.

When comparing the temperatures profiles at one-half the time to peak temperature to those at the peak temperature, more deviation between the profiles and clearer reduction of temperatures are observed at defects for the figures at one-half the time to peak temperature. For example, the defects at 14 ft and at 20 ft can be observed better at one-half the time to peak temperatures profiles in Figure 103, Figure 104, and Figure 105 than at the peak temperatures profiles, where the reduction in temperature is higher at the one-half the time to peak temperature. This is the reason why in Figure 106, only the temperatures' profiles at one-half the time to peak temperature are shown for the odd, even, and all the wires. Figure 106 shows a clear reduction in temperature around 14 ft and 20 ft for the odd, even, and all the wires.

Furthermore, the added cuttings at the bottom of casing between the rebar cage and the casing over quarter of the annulus circumference is located at depth of 3.5 ft. Therefore, the odd wire 3 shows a reduction at depth of 3.5 ft (bottom of casing) and wires 2 and 3 shows a reduction in the even wires at the same depth, similar in all the wires for wires 3, 4, and 5 indicating that there is a minor defect at this location. The research team has decided that this defect is the rock cutting, and therefore, it is detected. However, it should also be noted that this reduction is minor and not similar to those at 14 ft and 20 ft depth. There was no preplanning to create a rebar shift. However, because Consultant A have already concluded a rebar cage shifting, the research team thought it might be due to installation of the rebar cage, and therefore, wanted to further investigate it. From 0 ft to 3 ft, it can be seen that the opposite wires have shifted from largest to smallest temperature. For example, in the odd wires, wires 3 had the largest temperature from 0 ft to 1 ft and then became the lowest temperature compared to wire 6 which is in the opposite location of wire 3 that has the second lowest temperature from 0 ft to 1 ft and then became the largest temperature. This behavior can also

be seen in the odd wires 1 and 4 and in all the wires between wires 7-9 and 12-2. Consultant A also found another rebar shift from depth of 10 ft to the bottom of the drilled shaft. Figure 106 doesn't show a clear rebar shift from depth of 10 ft but it shows a rebar cage shift from around 20 ft to the bottom, where for the odd wires, a shift between wires 5 and 2 is found, for the even wires a shift between wires 5 and 1-2 is found, and for all the wires a shift between 9-10 and 2-4 is found. The change in diameter of the drilled shaft from 72 in. to 55 in. at the start of the rock socket at depth of 8.5 ft couldn't be detected by any wire for the odd, even, or all wires. There are few wires that showed a slight reduction in temperature at depth of 5.5 ft, which is the location of the tremie pipe raise of 1.5 ft, such as wire 5, 6, and 11-12 in the odd, even, and all the wires, respectively. However, this reduction of one of the wires could not be used as evidence of a defect. Lastly, it is important to note that using double the required number of thermal wires in TIP testing didn't provide any additional insights to the integrity of the shaft. Therefore, there is no need to use more than one thermal wire per foot of diameter (see Appendix F for IDOT specifications).

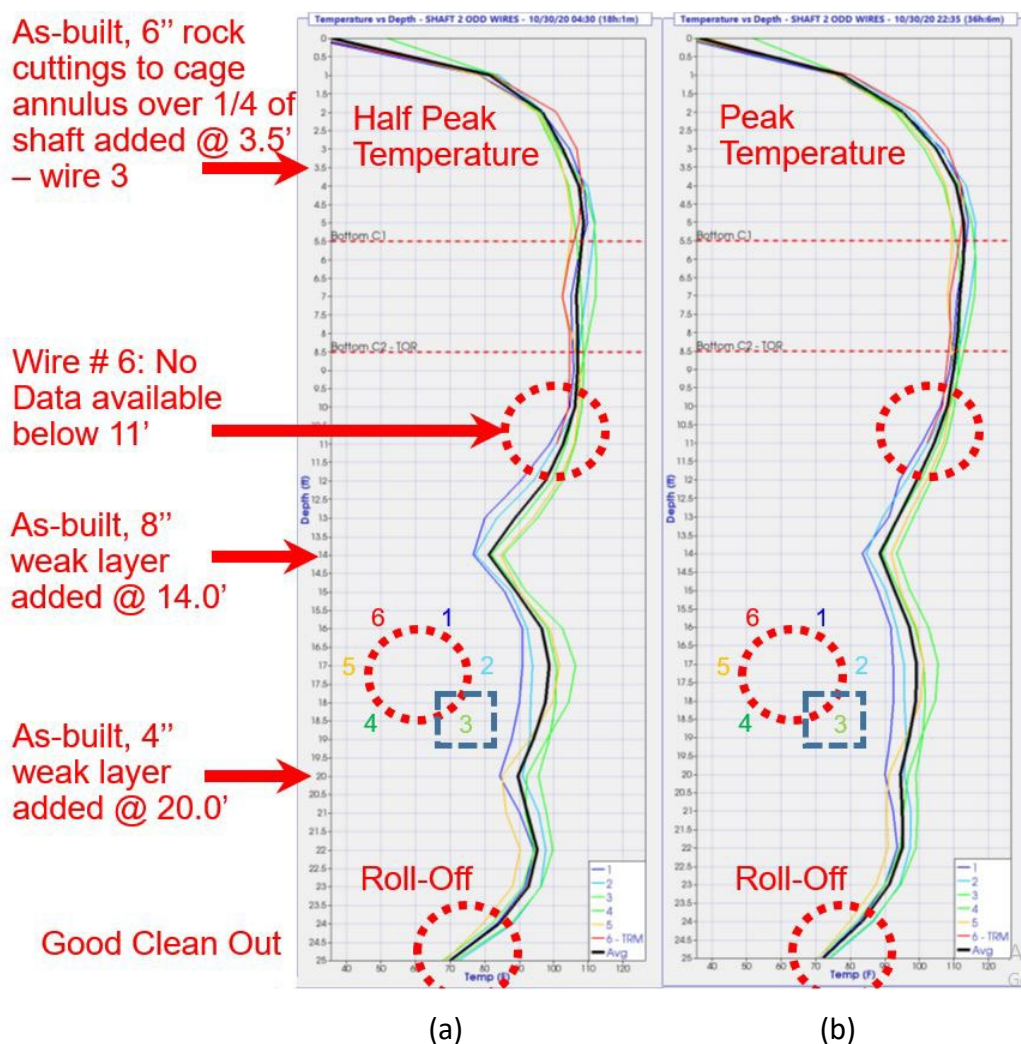


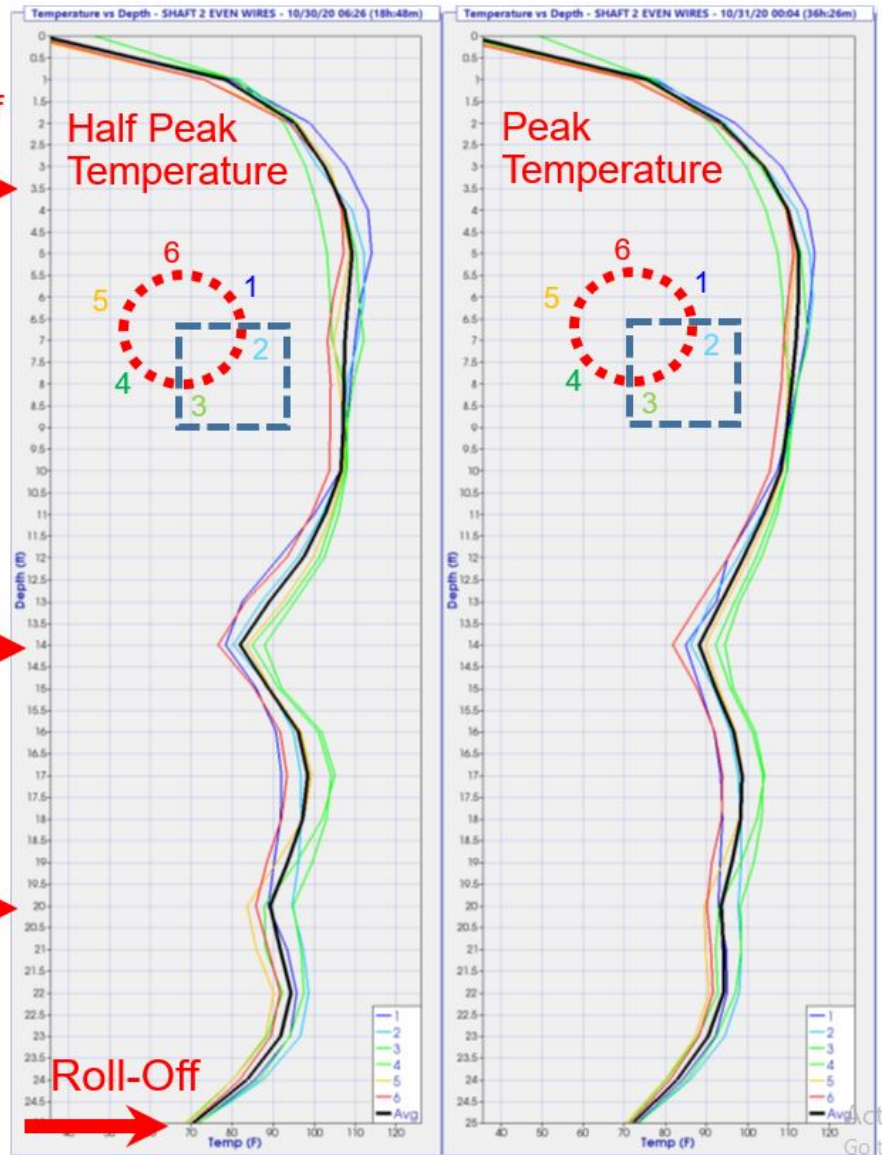
Figure 103. Graph. Temperature versus depth profiles for six odd wires in shaft #2: (a) at one-half time to peak temperature and (b) at peak temperature with red added arrows showing the location of installed defects.

As-built, 6" rock cuttings to cage annulus over 1/4 of shaft added @ 3.5' – wires 2&3

As-built, 8" weak layer added @ 14.0'

As-built, 4" weak layer added @ 20.0'

Good Clean Out



(a)

(b)

Figure 104. Graph. Temperature versus depth profile for the six even wires in test drilled shaft #2: (a) at one-half time to peak temperature and (b) at peak temperature with red added arrows showing the location of installed defects.

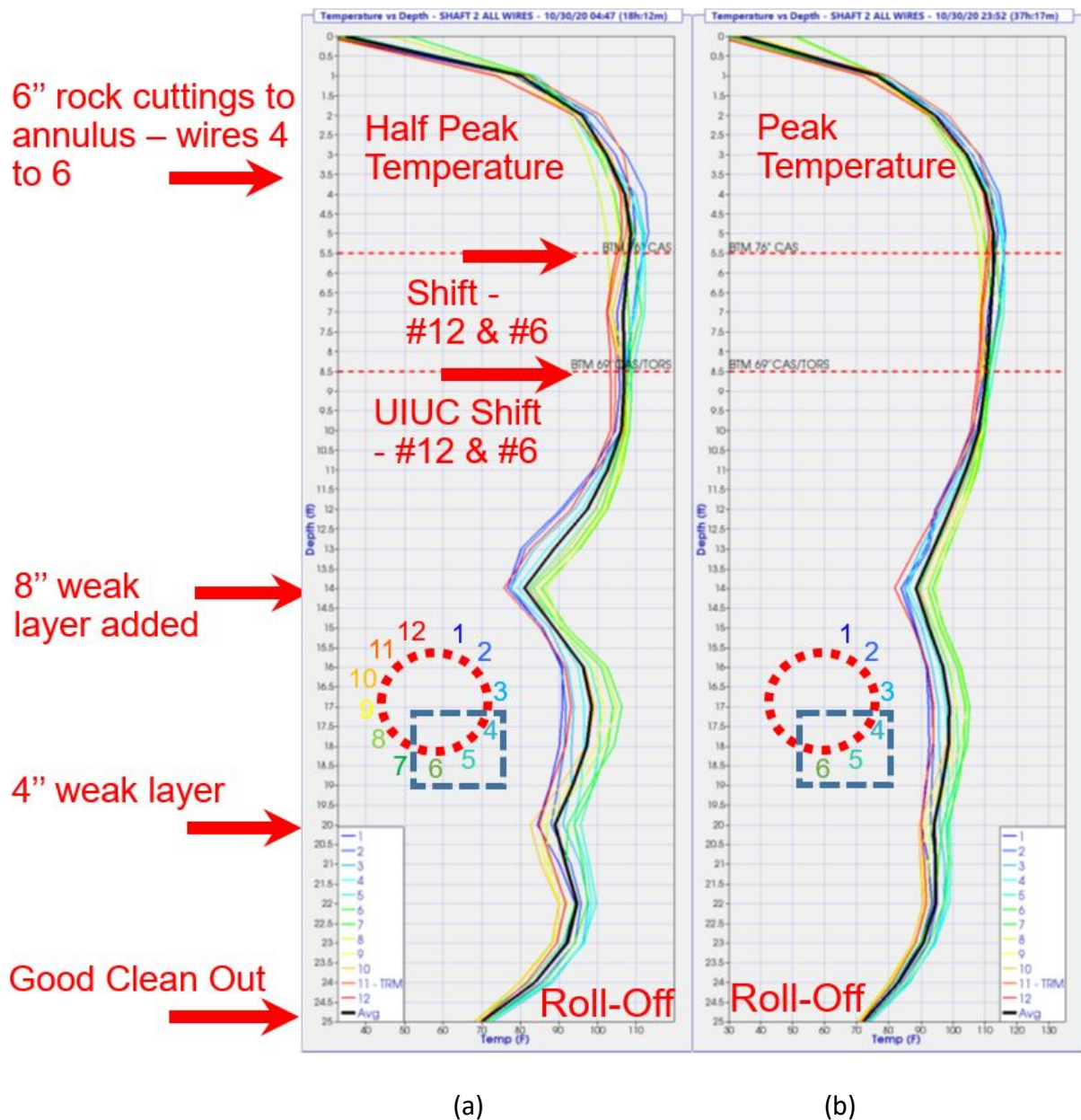


Figure 105. Graph. Temperature versus depth profile for all the twelve wires in test drilled shaft #2: (a) at one-half time to peak temperature and (b) at peak temperature with red added arrows showing the location of installed defects.

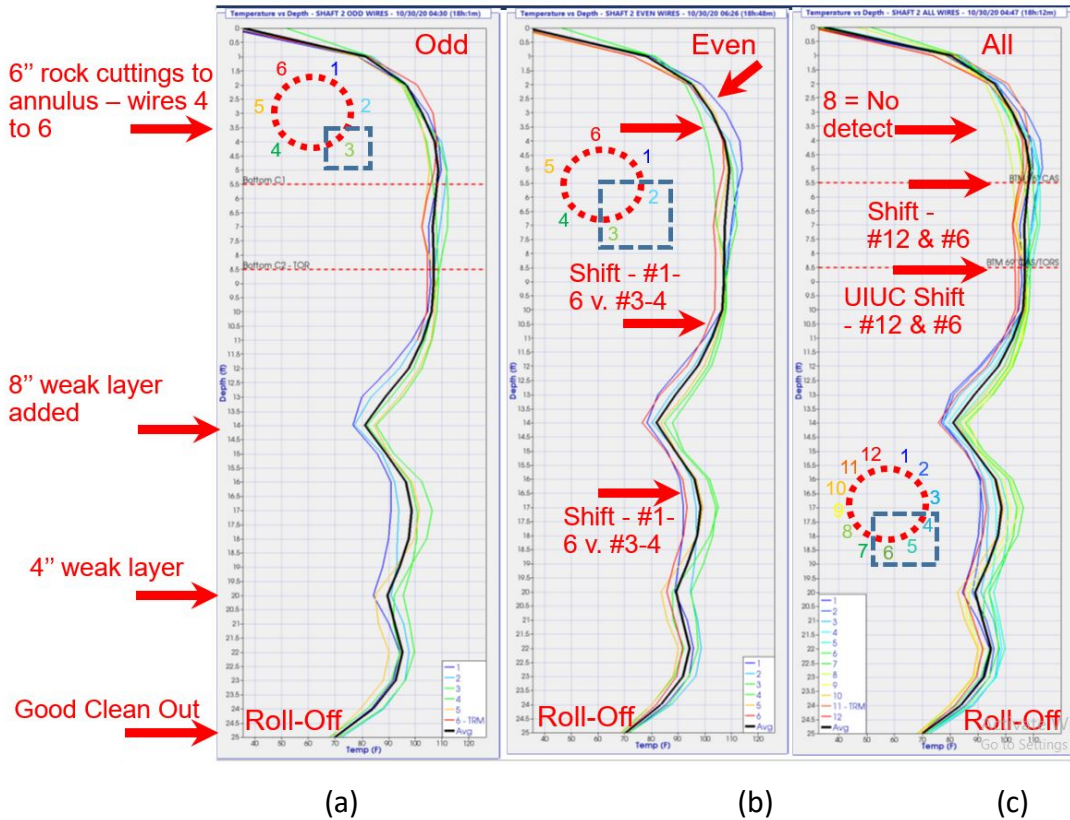


Figure 106. Graph. One-half time to peak temperature profiles for test drilled shaft #2 for: (a) odd wires, (b) even wires, and (c) all wires.

UIUC'S INTERPRETATION OF CSL RESULTS

UIUC's Interpretation of Consultant B's CSL Results

Figure 107 through Figure 111 show the Consultant B testing of the CSL performed on test drilled shaft #2 and used by the research team to assess the integrity of this shaft. These figures show the relative energy with FAT for different combinations between different tubes, where a sketch of the tube configuration is shown at the top of FAT and relative energy profiles. Figure 107(a), Figure 107(b), and Figure 107(c) show the FAT and relative energy profiles between access tubes 1-2, 1-3, and 1-4, respectively. Similarly, Figure 108, Figure 109, Figure 110, and Figure 111 show the FAT and relative energy profiles between the rest of access tubes in test shaft #2.

All the figures show a clear reduction in the relative energy (see blue line in Figure 107 through Figure 111) around 14 ft and 20 ft depths, except for profile 1-5 in Figure 108(a), which doesn't show a clear reduction of the relative energy at depth of 14 ft. The FAT profiles are not as indicative of these two defects as that of the relative energy profiles, where, in general only a small increase in FAT is observed at one of the defects rather than at both defects. However, in some tube configurations, the increase in FAT is well observed. For example, profile 1-2 and 1-3 in Figure 107, profile 2-6 in Figure 109, and profile 4-5 show a clear increase in FAT at around depth of 14 ft. Anomaly Zones A, B, and C (Classes A, B, and C) criteria are also included in all of these figures, where class C (highly

abnormal) is shown in profiles around 14 ft depth except for profiles 2-4 and 2- 5 in Figure 109, 3-6 in Figure 110, and 4-6 in Figure 111, where these profiles show class B (conditionally acceptable). Furthermore, profile 1-5 in Figure 108 shows that around 14 ft, the class is A (acceptable). Around 20 ft, class C is only shown in profile 1-4 in Figure 107, 1-5 in Figure 108, and 4-5 in Figure 111. Profile 2-6 in Figure 109, and profiles 3-4, 3-5, and 3-6 in Figure 110 show class A around 20 ft, and the rest of profiles show class B. Some of the profiles show a reduction in the relative energy at the bottom of test shaft (depth of 25 ft) with class B, even though no preplanned defect was created there and the drilled shaft had a good base clean out. This is why in Table 9 in Chapter 5, Consultant B had an inconclusive interpretation about a defect at the bottom of drilled shaft.

None of the CSL profiles show any indication of a defect around 3.5 ft, which is where a 6 in. rock cutting defect was created at about quarter of the annulus circumference between the temporary casing the rebar cage. This is expected because this defect is outside the rebar cage and because CSL can only detect defects between tubes (inside the rebar cage). The tremie pipe raise at 5.5 ft depth was also not detected by any of the CSL profiles. None of the rebar cage shifting that was observed by Consultant A based on TIP data was detected by Consultant B's CSL data, which is also expected because any potential shifting of the rebar cage is not expected to be detected by CSL because CSL measures the sonic pulses between CSL access tubes and can't detect what is outside the rebar cage.

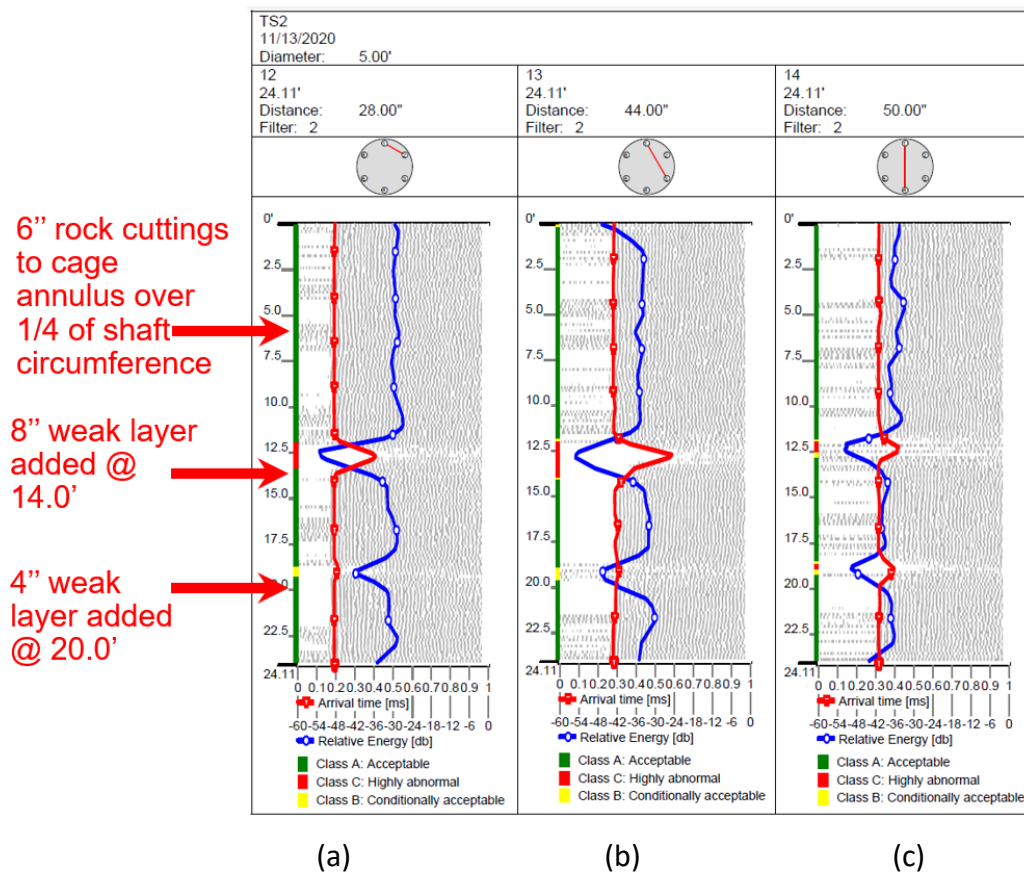
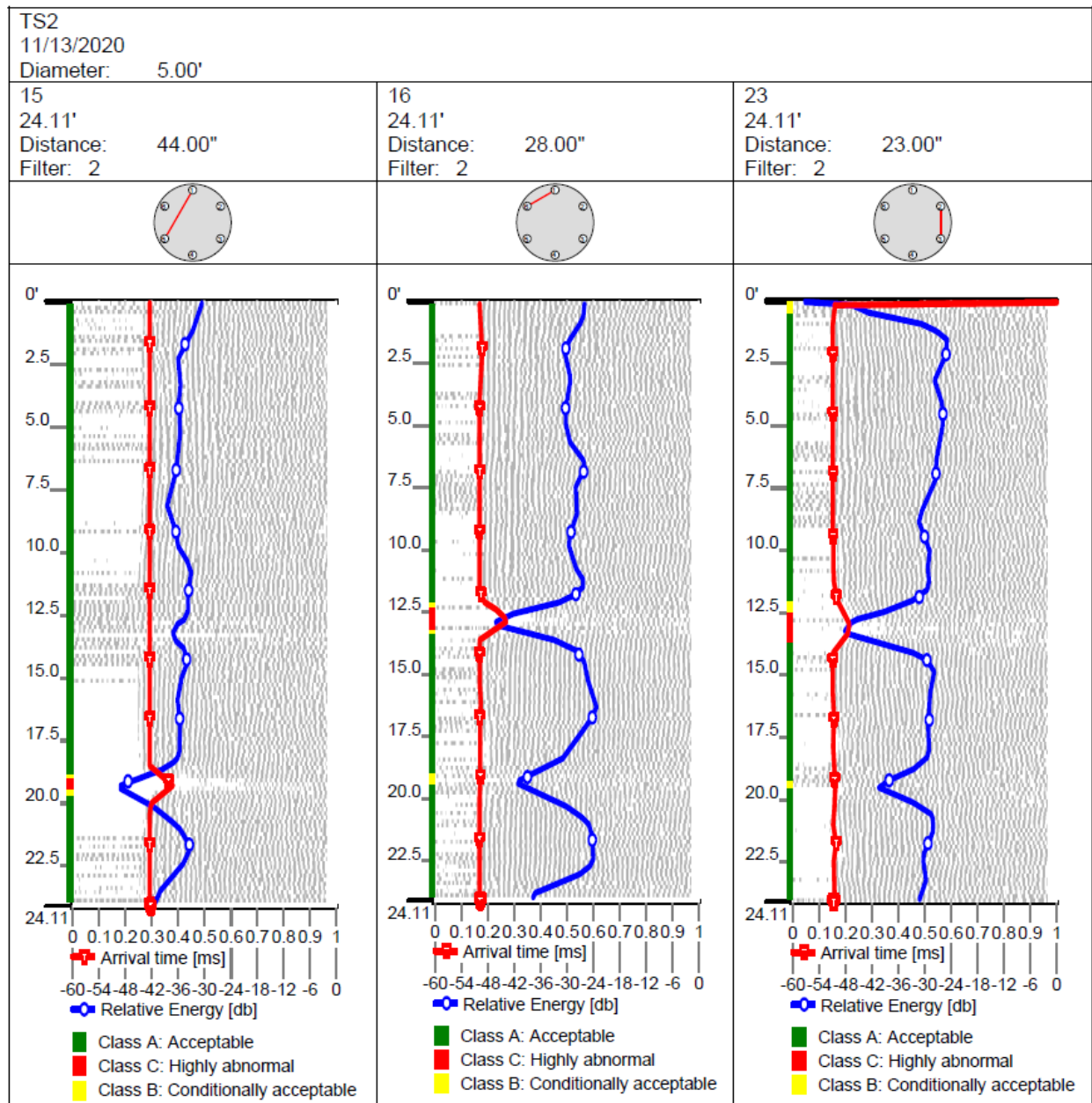


Figure 107. Graph. Consultant B's CSL results for test drilled shaft #2 for: (a) profile 1-2, (b) profile 1-3, and (c) profile 1-4 with red arrows showing the location of installed defects.

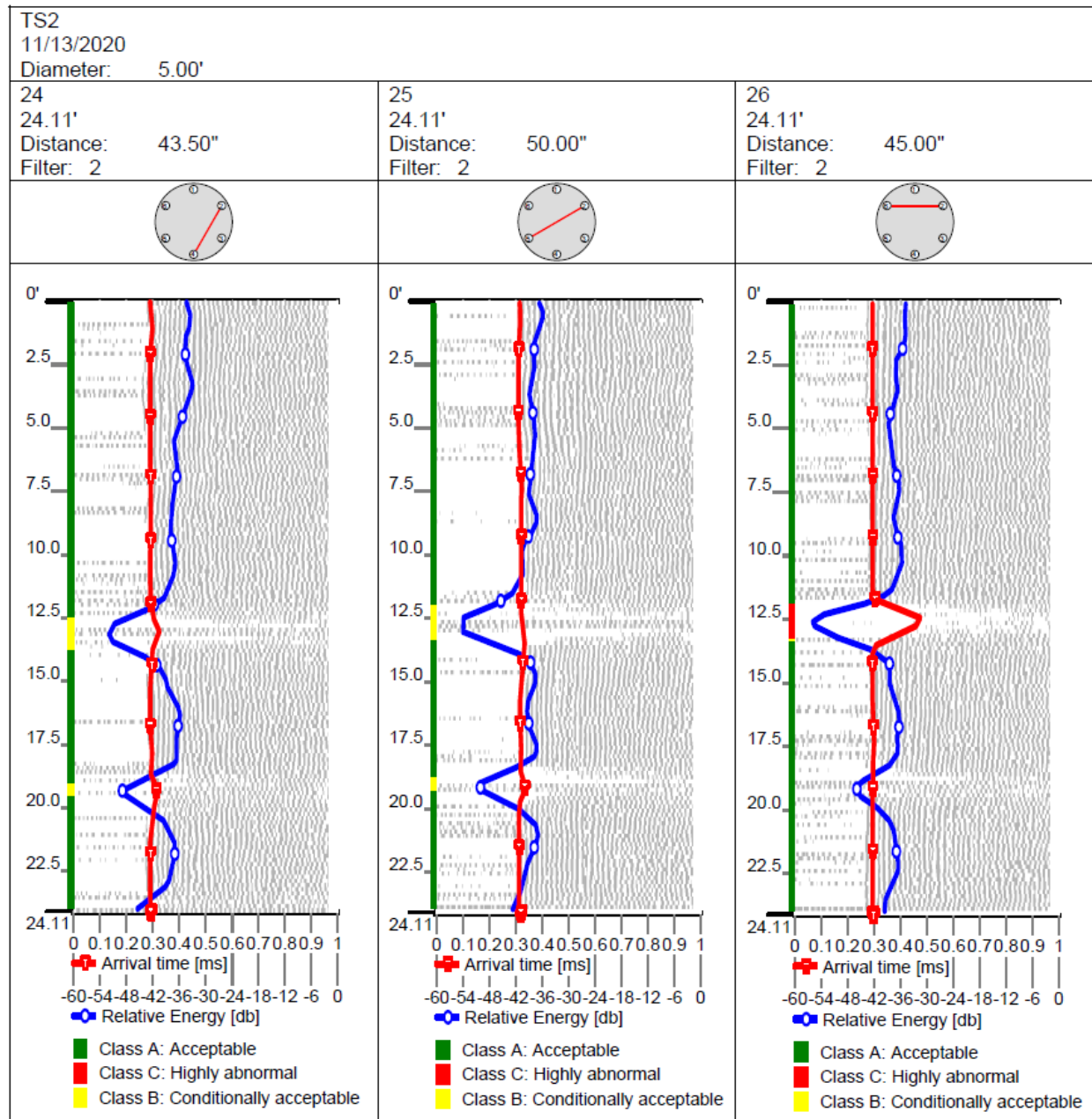


(a)

(b)

(c)

Figure 108. Graph. Consultant B CSL results for test drilled shaft #2 for: (a) profile 1-5, (b) profile 1-6, and (c) profile 2-3.

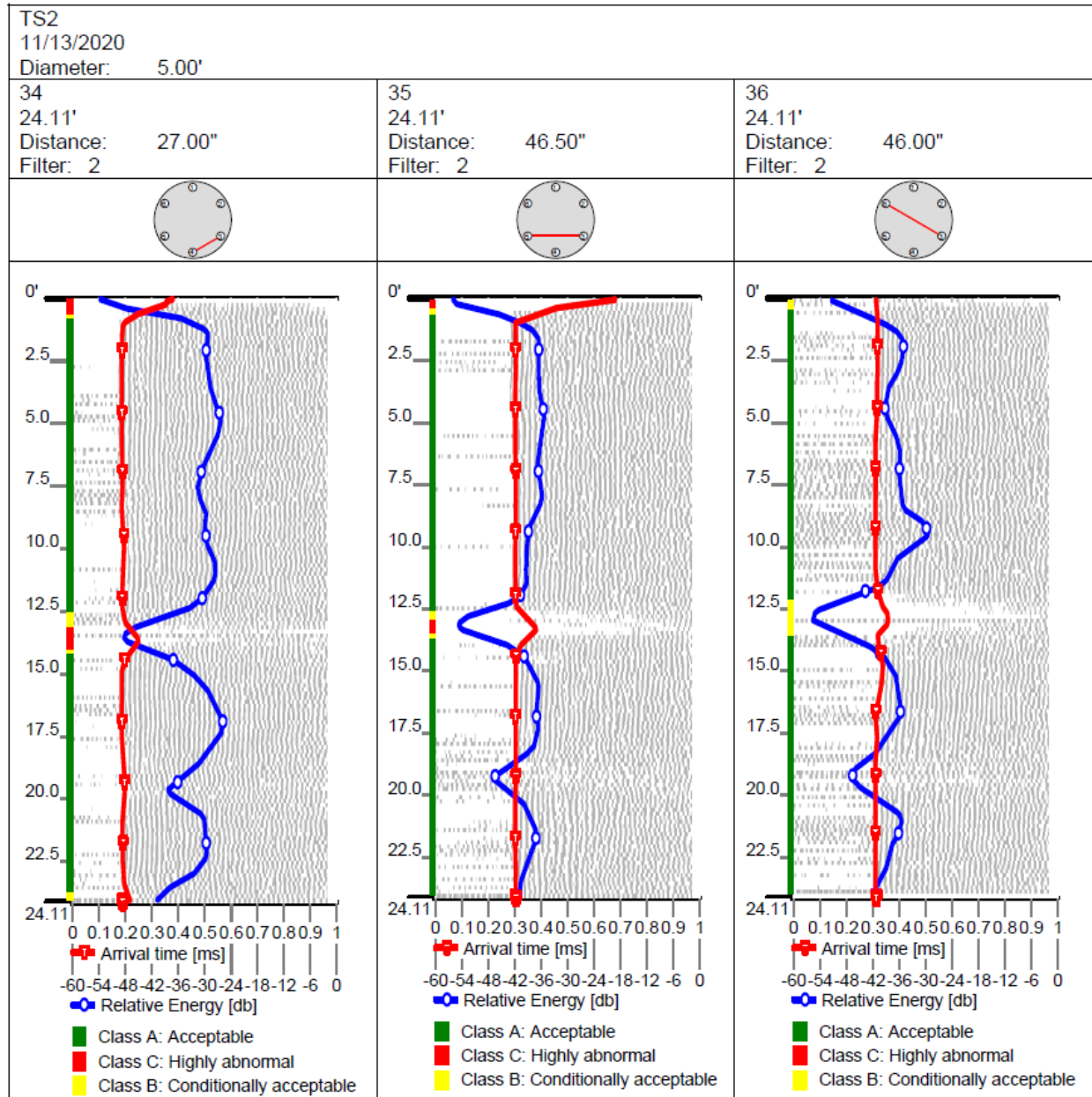


(a)

(b)

(c)

Figure 109. Graph. Consultant B CSL results for test drilled shaft #2 for: (a) profile 2-4, (b) profile 2-5, and (c) profile 2-6.



(a)

(b)

(c)

Figure 110. Graph. Consultant B CSL results for test drilled shaft #2 for: (a) profile 3-4, (b) profile 3-5, and (c) profile 3-6.

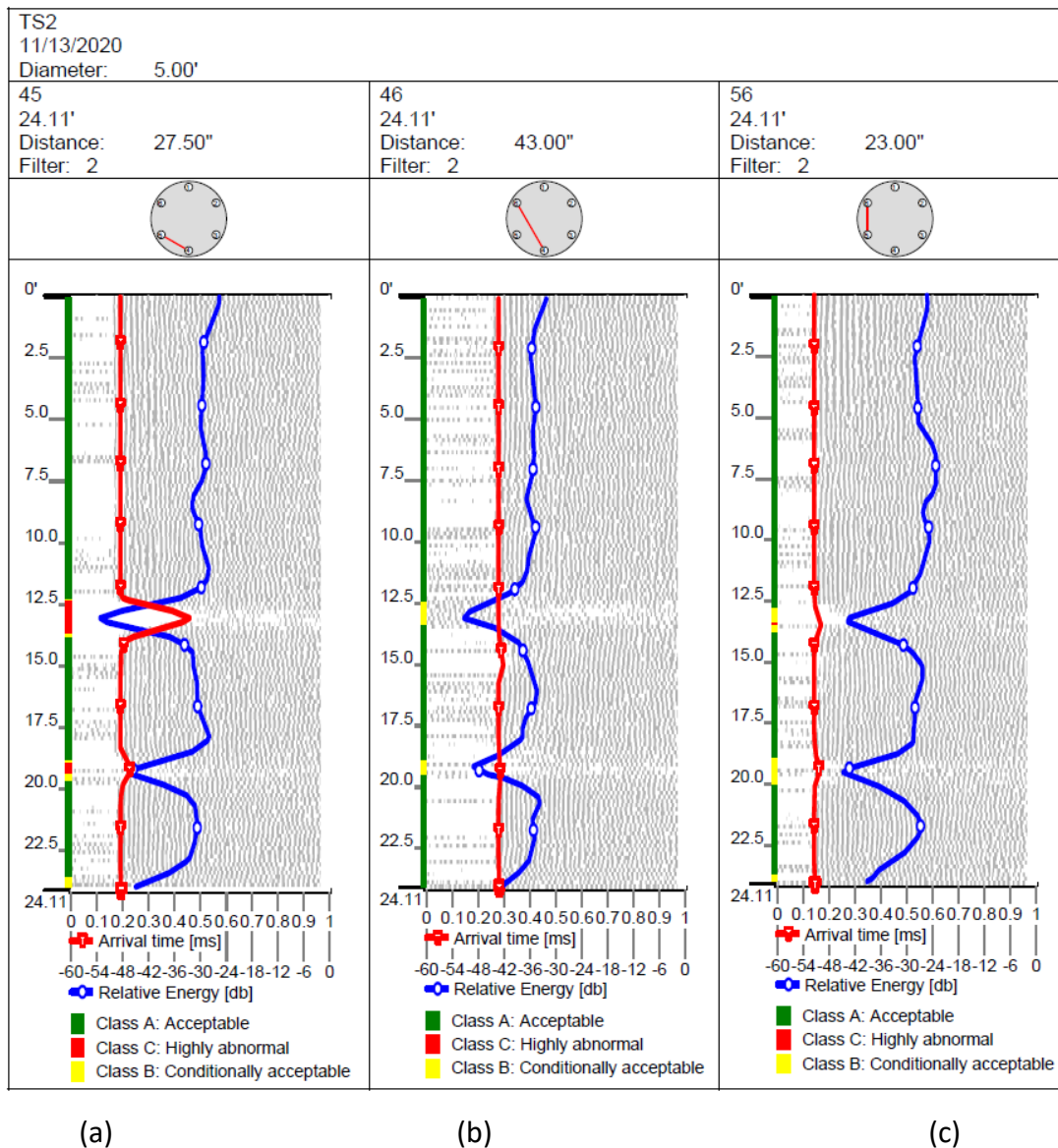


Figure 111. Graph. Consultant B CSL results for test drilled shaft #2 for: (a) profile 4-5, (b) profile 4-6, and (c) profile 5-6.

UIUC's Interpretation of Consultant A's CSL Results

Figure 112 through Figure 119 show the Consultant A data of the CSL performed on test drilled shaft #2 and used by the research team to assess the integrity of this shaft. As previously mentioned in Chapter 5, the figure on the left contains the FAT and relative energy profiles and the right side is the “waterfall diagram” that graphically presents the waterfall diagram, where a sketch of the tube configuration is shown at the top. The waterfall diagram shows the positive amplitudes of the record in black and the negative amplitudes in green of the raw data as a function of time. The waterfall diagram is a clearer representation of concrete quality over depth because the blank locations indicate much weaker material. Figure 112(a) and Figure 112(b) show the FAT and relative energy profiles between access tubes 1-2 and 1-6, respectively. Similarly, Figure 113, Figure 114, Figure 115,

Figure 116, Figure 117, Figure 118, and Figure 119 show the FAT and relative energy profiles between the rest of access tubes in test shaft #2. All the figures show a clear reduction in the relative energy around 14 ft and 20 ft depths. Similar to the Consultant B data, FAT profiles are not as indicative of these two defects as that of the relative energy profiles. Generally, only a small increase in FAT is observed at one of the defects rather than at both defects. However, in some profiles, the increase in FAT is well observed. For example, all FAT profiles show a clear increase in FAT at around depth of 14 ft. However, even though almost all the profiles also show an increase of FAT at around 20 ft depth, the increase is not as large as that observed at about 14 ft. Observing the waterfall diagrams, the discontinuity in the waterfall diagram is observed at 14 ft and at 20 ft depth in all figures with the gap at 14 ft being larger than that at 20 ft. This is expected because the defect created at 14 ft has a thickness of 8 in. which is larger than that created at 20 ft with being only 4 in.

Similar to the Consultant B results, some of the profiles show a reduction in the relative energy or a combination of a reduction in relative energy and an increase in FAT at the bottom of the drilled shaft even though no preplanned defect was created there and the drilled shaft had a good base clean out. No indication of a defect is shown at 3.5 ft, which is where a 6 in. rock cutting defect was created at about quarter of the annulus circumference between the temporary casing the rebar cage. No indication of a defect is shown also at 5.5 ft, which is where a 1.5 ft tremie pipe raise occurred, and none of the rebar cage shifting that was observed by Consultant A based on TIP data was detected herein by CSL data in any of the profiles which is also expected because any potential shifting of the rebar cage is not expected to be detected by CSL because CSL measures the sonic pulses between CSL access tubes and can't detect what is outside the rebar cage.

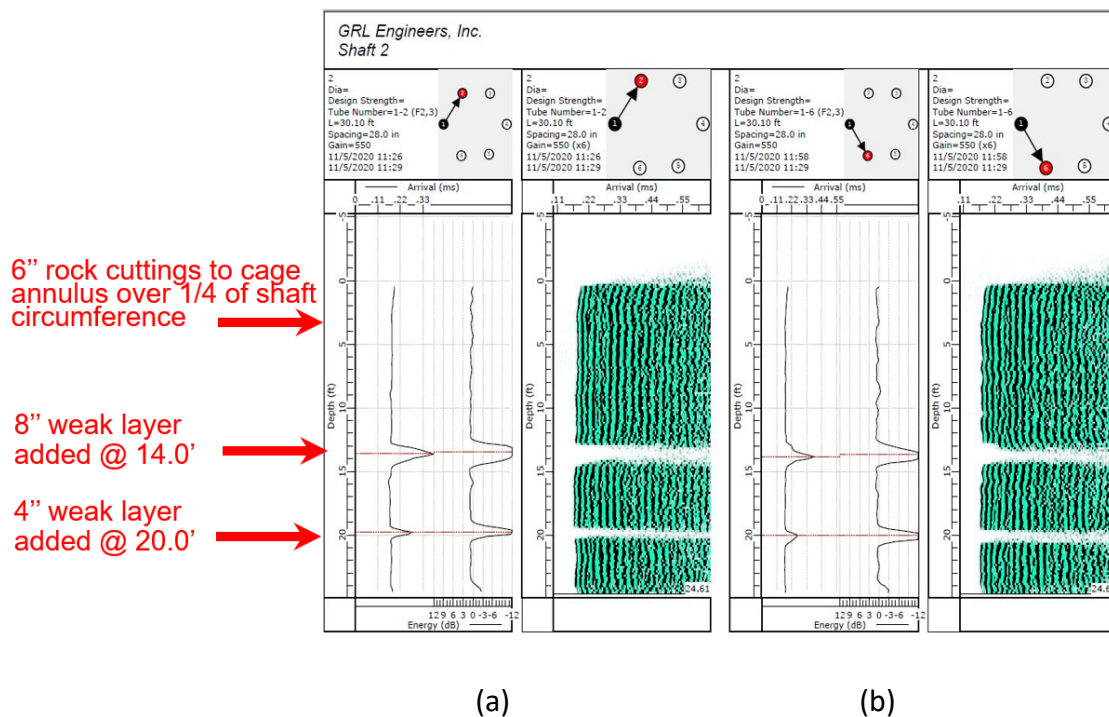


Figure 112. Graph. Consultant A's CSL results for test drilled shaft #2 for: (a) profile 1-2 and (b) profile 1-6 with red arrows showing the location of installed defects.

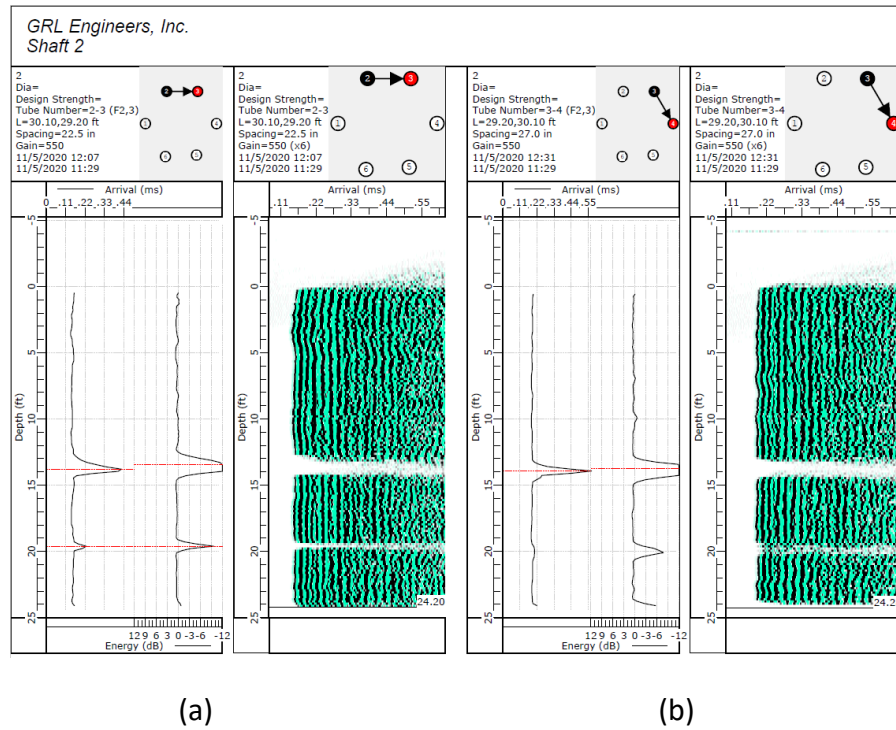


Figure 113. Graph. Consultant A's CSL results for test drilled shaft #2 for:
(a) profile 2-3 and (b) profile 3-4.

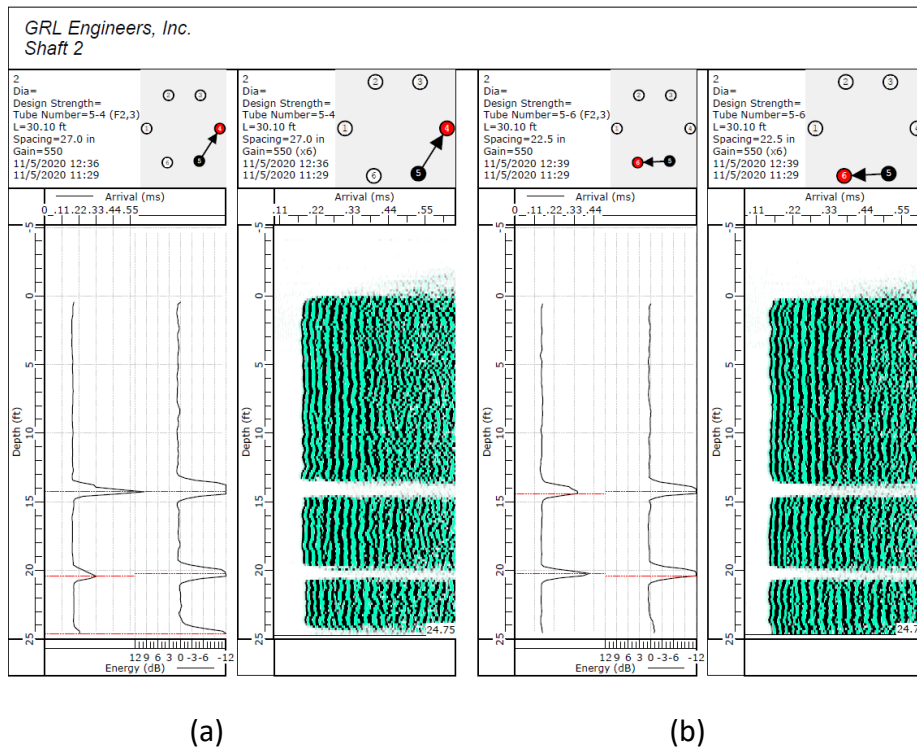


Figure 114. Graph. Consultant A CSL results for test drilled shaft #2 for:
(a) profile 5-4 and (b) profile 5-6.

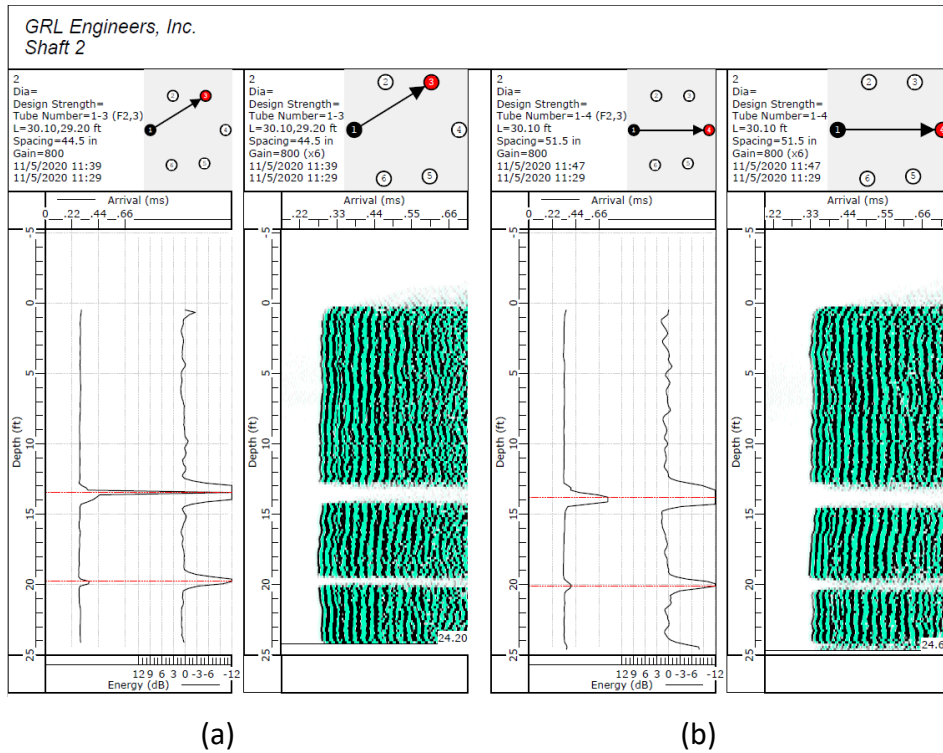


Figure 115. Graph. Consultant A CSL results for test drilled shaft #2 for:
(a) profile 1-3 and (b) profile 1-4.

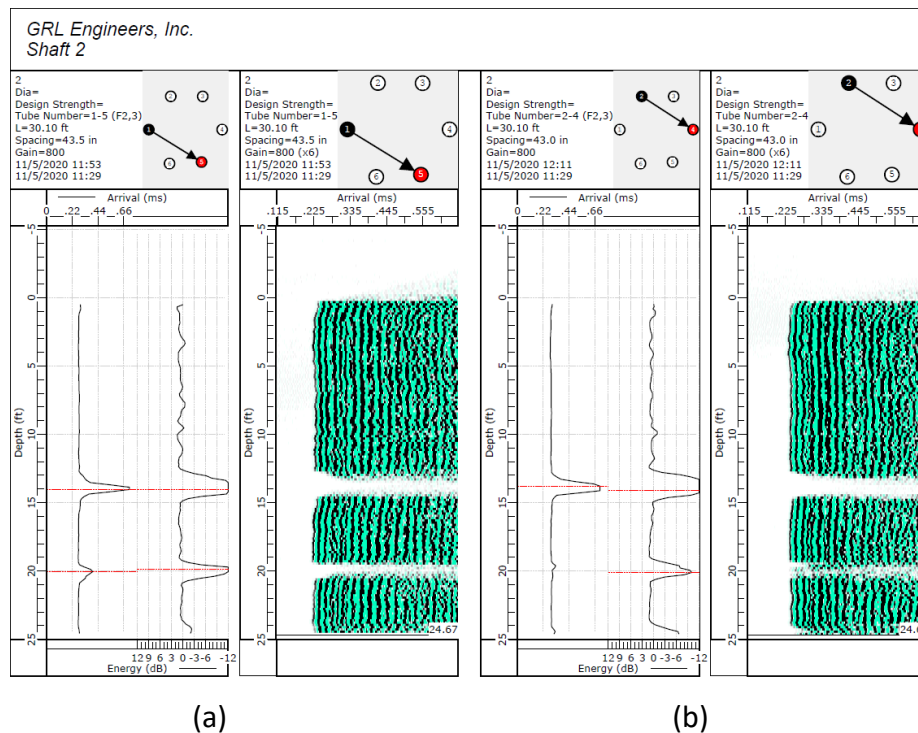


Figure 116. Graph. Consultant A CSL results for test drilled shaft #2 for:
(a) profile 1-5 and (b) profile 2-4.

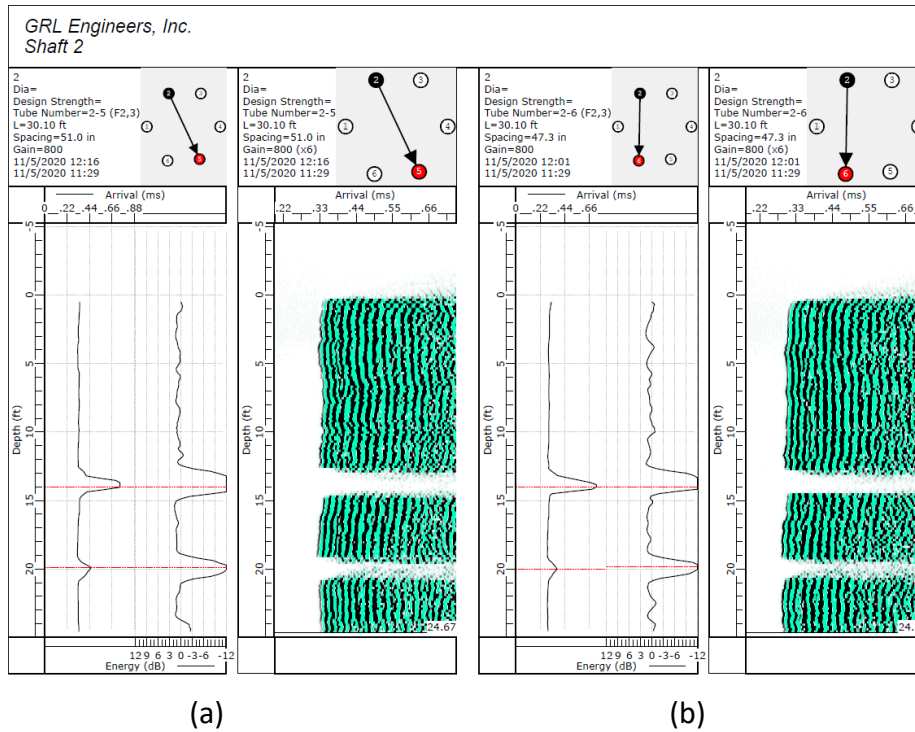


Figure 117. Graph. Consultant A CSL results for test drilled shaft #2 for:
(a) profile 2-5 and (b) profile 2-6.

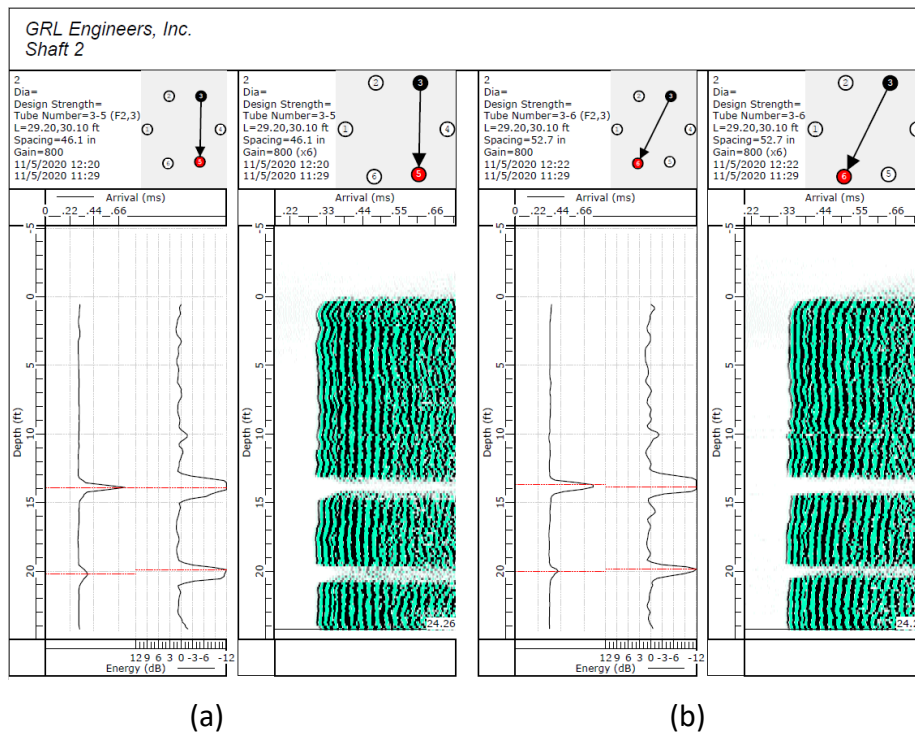


Figure 118. Graph. Consultant A CSL results for test drilled shaft #2 for:
(a) profile 3-5 and (b) profile 3-6.

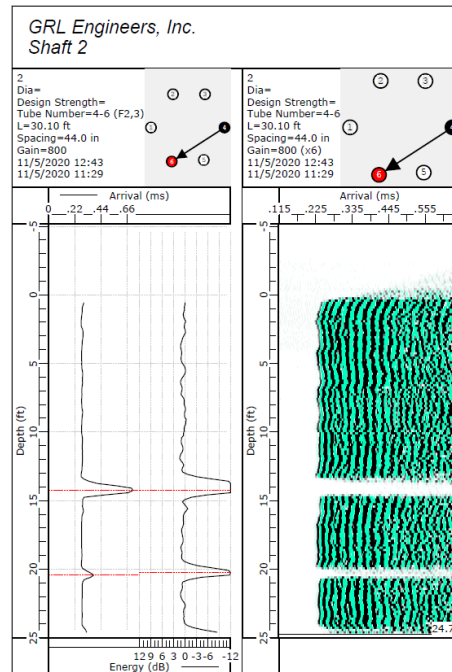


Figure 119. Graph. Consultant A CSL results for test drilled shaft #2 for profile 4-6.

CORING OF TEST SHAFT #2

Figure 120 shows the cores obtained from coring test drilled shaft #2 and the observed defect between depths of 13.5 and 14.0 ft. Figure 121 shows a close-up photograph of the two defects observed during concrete coring of test drilled shaft #2.



Figure 120. Photo. Cores obtained from coring test drilled shaft #2 showing the start and end of a defect between depths of 13.5 and 14.0 ft (see yellow arrows).

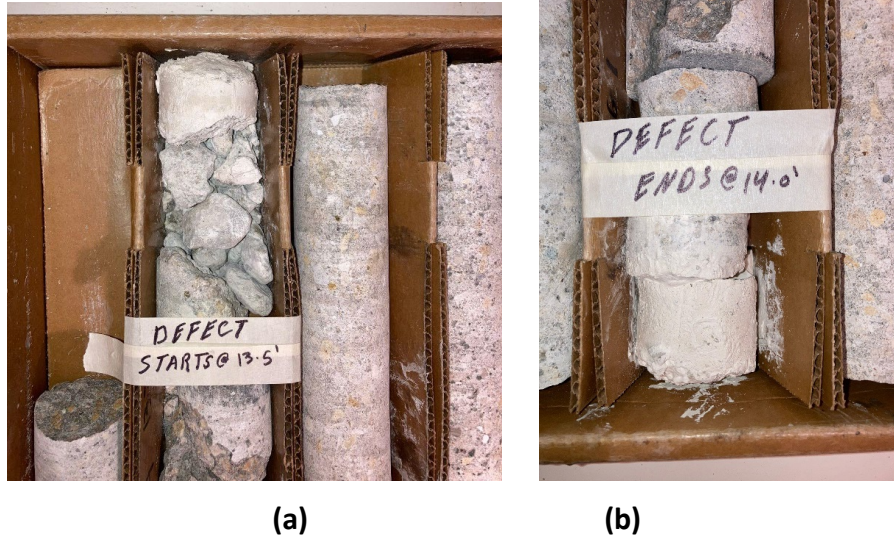


Figure 121. Photo. Close-up photographs of: (a) start of defect at 13.5 ft and (b) end of defect at 14.0 ft in test drilled shaft #2.

INSTALLATION RECORDS

Figure 122 shows a sketch of the TIP wires configuration with wire-wire distances at the bottom of the cage, the serial number for each wire, and general drilled shaft information, while Table 36, Table 37, and Table 38 show the actual distance measurements that were taken by the research team between wires for all wires, even numbered wires, and odd numbered wires, respectively.

THERMAL FIELD LOG

Project R27-188
Pier No. _____

Date Placed: 10/28/2020
Shaft No. 2

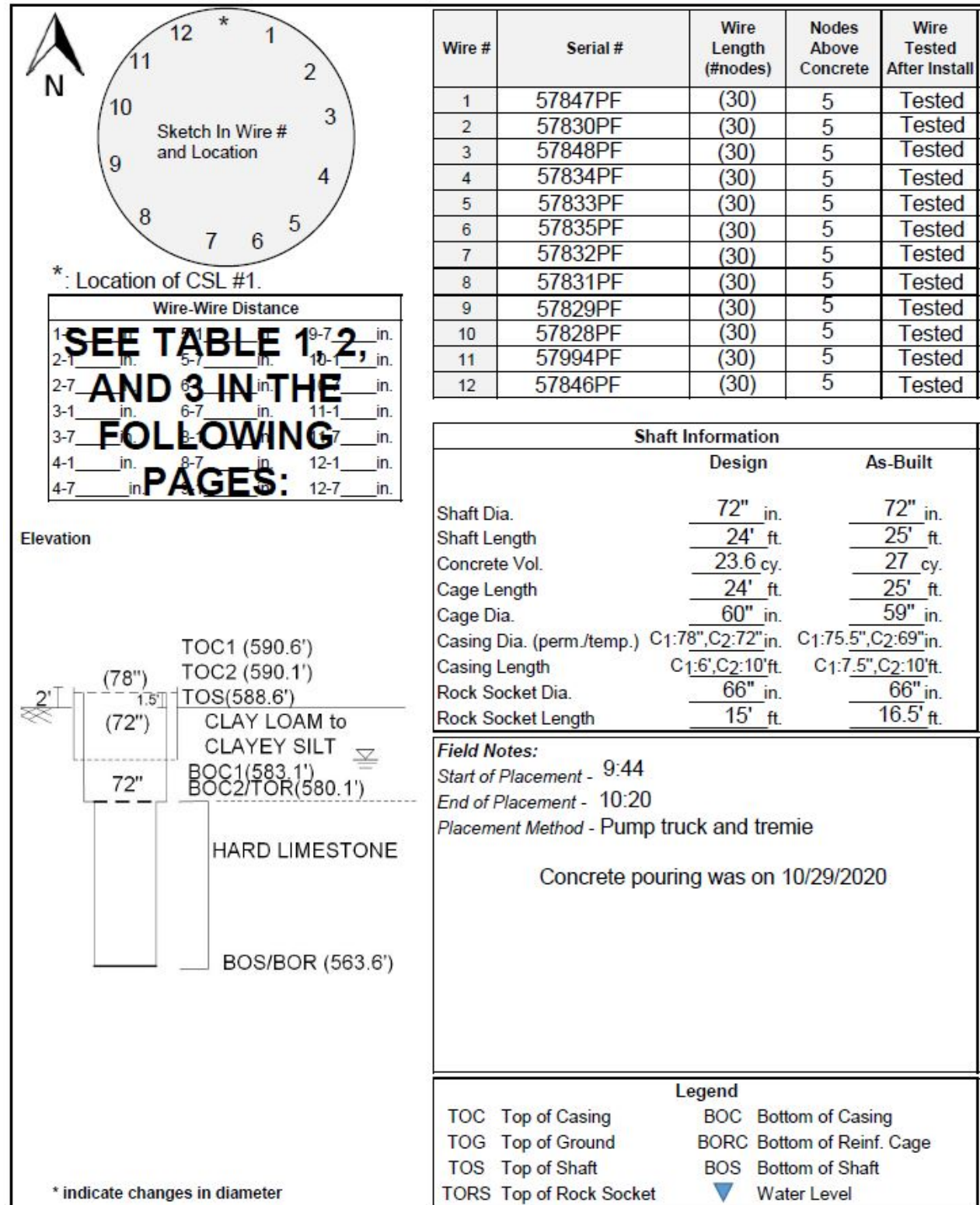


Figure 122. Illustration. TIP installation log for test drilled shaft #2.

Table 36. All Wire-Wire Distances for the 12 TIP Wires

Wire Number	Number	Distance (inch)	Wire Number	Number	Distance (inch)
1	2	16	2	8	57.25
1	3	30.5	2	9	54.5
1	4	38.25	2	10	51.5
1	5	48.5	2	11	42.75
1	6	55.25	2	12	30
1	7	57.5	3	4	10
1	8	54.75	3	5	24.25
1	9	48	3	6	38
1	10	42.25	3	7	48.75
1	11	30	3	8	55.25
1	12	14.75	3	9	56.75
2	3	15.5	3	10	56.25
2	4	24.75	3	11	51
2	5	37.75	3	12	41.75
2	6	48.25	4	5	14.75
2	7	55.5	4	6	30.25
			4	7	43
Wire Number	Number	Distance (inch)	Wire Number	Number	Distance (inch)
4	8	52.25	6	12	56.75
4	9	56	7	8	17.25
4	10	57.5	7	9	30.5
4	11	55.5	7	10	38.75
4	12	47.75	7	11	48.75
5	6	16	7	12	54.5
5	7	31.25	8	9	14.75
5	8	43.75	8	10	24.25
5	9	51.5	8	11	37
5	10	55.75	8	12	47
5	11	56.5	9	10	9.75
5	12	54.5	9	11	24.5
6	7	16.25	9	12	37.75
6	8	32	10	11	15.75
6	9	43.25	10	12	30.25
6	10	49.75	11	12	15.75
6	11	56.25			

Table 37. Even-Even Wire-Wire Distances for the 12 TIP wires

Wire Number	Number	Distance (inch)
2	4	24.75
2	6	48.25
2	8	57.25
2	10	51.5
2	12	30
4	6	30.25
4	8	52.25
4	10	57.5
4	12	47.75
6	8	32
6	10	49.75
6	12	56.75
8	10	24.25
8	12	47
10	12	30.25

Table 38. Odd-Odd Wire-Wire Distances for the 12 TIP Wires

Wire Number	Number	Distance (inch)
1	3	30.5
1	5	45.8
1	7	57.5
1	9	48
1	11	30
3	5	24.25
3	7	48.75
3	9	56.75
3	11	51
5	7	31.25
5	9	51.5
5	11	56.5
7	9	30.5
7	11	48.75
9	11	24.5

Figure 123 shows a diagram of the typical access tube configuration including the CSL tube numbers and the CSL testing combination, temporary casing and drilled shaft diameter and the location of the rebar cage.

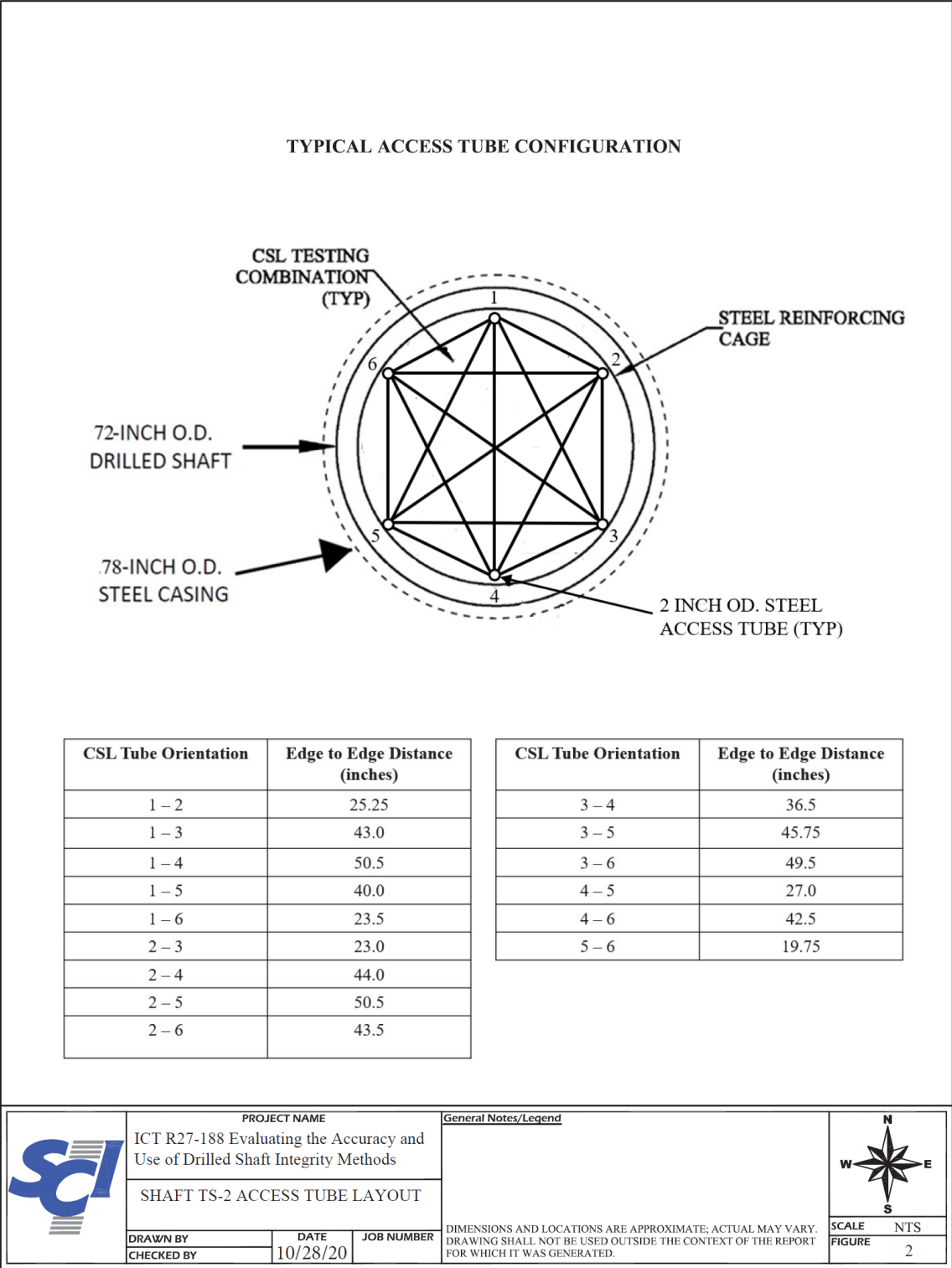


Figure 123. Illustration. CSL access tube configuration for test drilled shaft #2.

Figure 124 through Figure 129 show the excavation logs for test drilled shaft #2, where the soil was found to be grey silty clay with some brown silty clay and sandy silt up to a depth of 7 ft, after which, the auger hit the limestone at depth 7 ft. It was reported that the water table was first encountered at depth of 3.5 ft and was at depth of 2 ft at the end of excavation.

Project Name:		IDOT Test Shaft in Morris, IL		Page 1 of 8	
SCI Project No.:				Shaft Group:	
Contractor:		Illini Drilled Foundations		Shaft Number: 2	
Inspectors:		Tim Stark, J. Lin, A. Idreas and H.Wang- UIUC		Date: 10/28/20	
SCI Reviewer:					

Casing Information					Drilling Information
ID	OD	TOC Elev.	Length	BOC Elev,	
72"	78"	590.6'	7.5'	590.1'	Soil Auger Dia. (ft): 6.5
		590.1'	10'	580.1'	Rock Core Dia. (ft): 5.5
		580.1'	16.5'	563.6'	Gnd Surface Elev. (ft): 588.6
66"	No casing (rock socket)				Water Table Elev. (ft): 4.67"
					Reference Elev. (ft): 588.6
					Drilling Mud:
Notes:					

Depth (ft)	Elevation (ft)	Time		Soil Description and Notes
0	588.6	7:47	in	Partial Brown mixed with black silty clay and silty clay loam
0.75	587.85	7:49	out	
0.75	587.85	7:49	in	
1.5	587.1	7:52	out	Grey silty clay with some brown silty clay
1.5	587.1	7:52	in	
2.25	586.35	7:54	out	Grey silty clay
2.25	586.35	7:54	in	Grey silty clay
3	585.6	7:55	out	
3	585.6	7:55	in	Grey silty clay and brown silty clay
3.75	584.85	7:57	out	
3.75	584.85	8:00	in	First 78' casing in, Change to 72' auger, brown clay
3.75	584.85	8:01	out	
3.75	584.85	8:17	in	
5	583.6	8:19	out	Grey silty clay with sand
5	583.6	8:19	in	Grey clay silt to sandy silt
6	582.6	8:21	out	
6	582.6	8:21	in	Grey clay silt to sandy silt
6.5	582.1	8:22	out	
6.5	582.1	8:22	in	Grey silty sand to sandy silt and hit bedrock, put casing in
7	581.6	8:24	out	

Figure 124. Table. Excavation log #1 for test drilled shaft #2.

Figure 125. Table. Excavation log #2 for test drilled shaft #2.



SCI Engineering, Inc.

Project Name: IDOT Test Shaft in Morris, IL **Page** 3 **of** 8
SCI Project No.: _____ **Shaft Group:** _____
Contractor: Illini Drilled Foundations **Shaft Number:** 2
Inspectors: Tim Stark, J. Lin, A. Idreas and H. Wang- UIUC **Date:** 10/28/20
SCI Reviewer: _____

Casing Information					Drilling Information	
ID	OD	TOC Elev.	Length	BOC Elev.	Soil Auger Dia. (ft):	
72"	78"	590.6'	7.5	590.1'	Rock Core Dia. (ft):	
					Gnd Surface Elev. (ft):	
		590.1'	10'	580.1'	Water Table Elev. (ft):	
66"	No casing (shaft)	580.1'	16.5'	563.6'	Reference Elev. (ft):	
					Drilling Mud:	

Notes:

Depth (ft)	Elevation (ft)	Time		Soil Description and Notes
12.5	576.1	10:27	in	
13	575.6	10:34	out	
13	575.6	10:34	in	
13.3	575.3	10:44	out	
13.3	575.3	10:44	in	
13.3	575.3	10:50	out	switched to 42' auger
11.3	577.3	10:50	in	
14	574.6	10:58	out	
14	574.6	10:58	in	
14.4	574.2	11:08	out	
14.4	574.2	11:08	in	
15	573.6	11:18	out	
15	573.6	11:18	in	
16	572.6	11:42	out	
16	572.6	11:42	in	
17	571.6	11:57	out	
17	571.6	11:57	in	
17	571.6	11:59	out	switched to 66' auger
16	572.6	11:59	in	
16	572.6	12:13	out	

Figure 126. Table. Excavation log #3 for test drilled shaft #2.



SCI Engineering, Inc.

Project Name: IDOT Test Shaft in Decatur, IL **Page** 4 **of** 8
SCI Project No.: _____ **Shaft Group:** _____
Contractor: Illini Drilled Foundations **Shaft Number:** 2
Inspectors: Tim Stark, J. Lin, A. Idreas and H.Wang- UIUC **Date:** 10/28/20
SCI Reviewer: _____

Casing Information					Drilling Information	
ID	OD	TOC Elev.	Length	BOC Elev.		
72"	78"	590.6'	7.5	590.1'	Soil Auger Dia. (ft): _____	
					Rock Core Dia. (ft): _____	
					Gnd Surface Elev. (ft): _____	
					Water Table Elev. (ft): _____	
					Reference Elev. (ft): _____	
					Drilling Mud: _____	
66"	No casing (shaft)	590.1'	10'	580.1'		
		580.1'	16.5'	563.6'		

Notes: _____

Depth (ft)	Elevation (ft)	Time		Soil Description and Notes
16	572.6	12:13	in	Performed clean out
16	572.6	12:18	out	
16	572.6	12:18	in	
16	572.6	12:22	out	
16	572.6	12:22	in	Changed to core edge cutting
17	571.6	12:29	out	
17	571.6	12:29	in	
17	571.6	12:33	out	
17	571.6	12:33	in	Switched to 42" auger
17	571.6	12:46	out	
17	571.6	12:46	in	
18	570.6	12:54	out	
18	570.6	12:54	in	
18	570.6	12:56	out	
18	570.6	12:56	in	
19	569.6	13:02	out	
11.4	577.2	13:02	in	
20	568.6	13:07	out	
20	568.6	13:07	in	
21	567.6	13:13	out	

Figure 127. Table. Excavation log #4 for test drilled shaft #2.

Project Name: IDOT Test Shaft in Morris, IL **Page** 5 **of** 8
SCI Project No.: **Shaft Group:**
Contractor: Illini Drilled Foundations **Shaft Number:** 2
Inspectors: Tim Stark, J. Lin, A. Idreas and H.Wang- UIUC **Date:** 10/28/20
SCI Reviewer:

Casing Information					Drilling Information	
ID	OD	TOC Elev.	Length	BOC Elev,	Soil Auger Dia. (ft):	
72"	78"	590.6'	7.5	590.1'	Rock Core Dia. (ft):	
					Gnd Surface Elev. (ft):	
					Water Table Elev. (ft):	
					Reference Elev. (ft):	
					Drilling Mud:	
66"	No casing (shaft)	590.1'	10'	580.1'		
		580.1'	16.5'	563.6'		

Notes:

Depth (ft)	Elevation (ft)	Time		Soil Description and Notes
21	567.6	13:13	in	Performed clean out
23	565.6	13:19	out	
23	565.6	13:19	in	
24	564.6	13:24	out	
24	564.6	13:24	in	Changed to 66" auger
25	563.6	13:40	out	
25	563.6	13:40	in	
25	563.6	13:49	out	
18	570.6	13:49	in	
20	568.6	13:58	out	
20	568.6	13:58	in	
22	566.6	14:10	out	
22	566.6	14:10	in	
23	565.6	14:21	out	
23	565.6	14:21	in	
24	564.6	14:27	out	
24	564.6	14:27	in	Proceeded with cleanout
25	563.6	14:51	out	
25	563.6	14:51	in	
25	563.6	15:51	out	

Figure 128. Table. Excavation log #5 for test drilled shaft #2.

Project Name:	IDOT Test Shaft in Morris, IL	Page	6	of	8
SCI Project No.:		Shaft Group:			
Contractor:	Illini Drilled Foundations	Shaft Number:	2		
Inspectors:	Tim Stark, J. Lin, A. Idreas and H. Wang- UIUC	Date:	10/28/20		
SCI Reviewer:					

Type of Drilling Fluid	Reinforcing Cage
Bottom Cleanout Method	Shaft Plumbness Check/4ft
Time/Date Final Cleanout	Proper # Vertical Bars
Top of Rock Elevation (ft)	Proper # Horizontal Bars
Bottom of Rock Elevation (ft)	Side Spacers
Rock Socket Dia, (in)	Bottom Spacers
Shaft Bottom Elev. (ft)	Ties and Connections
Est. Shaft Bottom Dia. (ft)	

Inspector	Type	Time			
			Start (Prior to Steel Placement)		Test prior to Steel Placement
			Finish (Prior to Steel Placement)		
			Start (Prior to Concrete Placement)		Test prior to Concrete Placement
			Finish (Prior to Concrete Placement)		

Type:

V - Visual

S - Sounding

MS - Mini-SID

N

W

E

NOTES	S	Comments/Recommendations

Results:	Satisfactory	DS Foreman	Date/Time
	Unsatisfactory	SCI Inspector	

Figure 129. Illustration. Excavation log #6 for test drilled shaft #2.

The drilled shaft concrete placement log in Figure 130 shows that there were 3 concrete trucks used with a volume of 9 yd³ for each truck leading to a total concrete volume of 27 yd³ used for test drilled shaft #2. Figure 131 below shows the summary log for test drilled shaft #2.

DRILLED SHAFT CONCRETE PLACEMENT LOG																																	
Project Name:		IDOT Test Shaft in Morris, IL				Page		7 of 8																									
SCI Project No.:						Shaft Group:																											
Contractor:		Illini Drilled Foundations				Shaft Number:		2																									
Inspectors:		Tim Stark, J. Lin, A. Idreas and H.Wang- UIUC				Date:		10/28/20																									
<table style="width: 100%; border: none;"> <tr> <td style="width: 20%;">Placement Method</td> <td style="width: 10%; text-align: center;">☒ Tremie</td> <td style="width: 20%; text-align: center;">☐ Pumped</td> <td style="width: 15%;">Volume in Pump Truck</td> <td style="width: 5%; text-align: center;">#</td> <td style="width: 5%; text-align: center;">ID</td> <td style="width: 10%;">Length</td> <td style="width: 10%;">Vol.</td> </tr> <tr> <td></td> <td></td> <td></td> <td>Pump Truck Lines</td> <td></td> <td></td> <td></td> <td>yd³</td> </tr> <tr> <td></td> <td></td> <td></td> <td>Pump Truck Hopper</td> <td></td> <td></td> <td></td> <td>yd³</td> </tr> </table>										Placement Method	☒ Tremie	☐ Pumped	Volume in Pump Truck	#	ID	Length	Vol.				Pump Truck Lines				yd ³				Pump Truck Hopper				yd ³
Placement Method	☒ Tremie	☐ Pumped	Volume in Pump Truck	#	ID	Length	Vol.																										
			Pump Truck Lines				yd ³																										
			Pump Truck Hopper				yd ³																										
Ref. Elev.		588.6																															
TOC Elev.		590.6/590.1																															
TOS Elev.		588.6		Total Volume in Lines + Pump Truck				Σ = 9 yd ³																									
TOR Elev.		580.1																															
BOC Elev.		583.1/580.1		Time First Truck Batched:		9:20 am																											
BOR Elev.		563.6		Depth of Water per Hour Inside Shaft (Dry Hole Check):																													
BOS Elev.		563.6		Rebar Cage Top Elev (Start):		588.1		(Finish): 588.1																									
Truck No.	Concrete Volume (yd³)	Arrival Time	Start Time	Finish Time	Tremie Depth (ft)	Depth to Concrete before filling (ft)	Depth to Concrete after filling (ft)	Notes																									
1	9	9:34	9:44	10:06	23	25	17																										
2	9	9:50	10:12	10:29	18.5	17	8																										
3	9	10:06	10:51	10:20	11	8	0																										
<table style="width: 100%; border: none;"> <tr> <td style="width: 20%; text-align: right;">Temp Casing Removal</td> <td style="width: 10%; text-align: center;">OD</td> <td style="width: 10%; text-align: center;">Top Elev.</td> <td style="width: 10%; text-align: center;">Bot. Elev.</td> <td style="width: 10%; text-align: center;">Start</td> <td style="width: 10%; text-align: center;">Finish</td> <td style="width: 10%; text-align: center;">Rebar Cage</td> <td style="width: 10%;"></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td style="text-align: center;">Centered:</td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td style="text-align: center;">Re-Centered:</td> <td></td> </tr> </table>									Temp Casing Removal	OD	Top Elev.	Bot. Elev.	Start	Finish	Rebar Cage								Centered:								Re-Centered:		
Temp Casing Removal	OD	Top Elev.	Bot. Elev.	Start	Finish	Rebar Cage																											
						Centered:																											
						Re-Centered:																											
Notes: _____																																	

Figure 130. Table. Concrete pouring log for test drilled shaft #2.

Project Name:	IDOT Test Shaft in Morris, IL	Page	8	of	8
SCI Project No.:		Shaft Group:			
Contractor:	Illini Drilled Foundations	Shaft Number:	2		
Inspectors:	Tim Stark, J. Lin, A. Idreas and H.Wang- UIUC	Date:	10/28/20		

Date Cased	<u>10.29.2020</u>			
Date Opened		Casing Type		
Date Concrete Placed	<u>10.29.2020</u>	Casing Outside Diameter (OD) (ft)		
		Bot. Of Casing (BOC) Elev. (ft)		
Elev. (ft)		Top Of Casing (TOC) Elev. (ft)		
		Dia. of Rock Socket (ft)	<u>5.5</u>	
		Shaft Diameter (ft)	<u>6</u>	
		Ground Surface Elevation (ft)	<u>588.6</u>	
		Wet & Dry Shaft Length (ft)	<u>8.5</u>	
		Rock Socket Length (ft)	<u>16.5</u>	
		Top Of Shaft (TOS) Elevation (ft)	<u>588.6</u>	
		Bot. Of Shaft (BOS) Elevation (ft)	<u>563.6</u>	
		Constructed Shaft Length (ft)	<u>25</u>	
		Reinforcing Steel Cage Placed	<u>yes</u>	
		Volume of Concrete		
		Design Mix		
		Theoretical (VTh)	<u>23.6 yd³</u>	Actual (VP)
		OP (VP-VTh)		UP (VTh - VP)
		Duration (min)		

Legend:

TOC	Top Of Casing	Sand
TOG	Top Of Ground	
TOS	Top Of Shaft	Silt
TOR	Top Of Rock	
BOC	Bottom Of Casing	Clay
BOS	Bottom Of Shaft	
BOR	Bottom Of Rock	Rock

Contractor: Illini Drilled Foundations

Notes: _____

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APPENDIX E: TEST DRILLED SHAFT #3

SITE INVESTIGATION

Test drilled shaft #3 is located 0.3 miles North of Nelson Road in Grundy County, Illinois along IL-47 as shown in Figure 132.

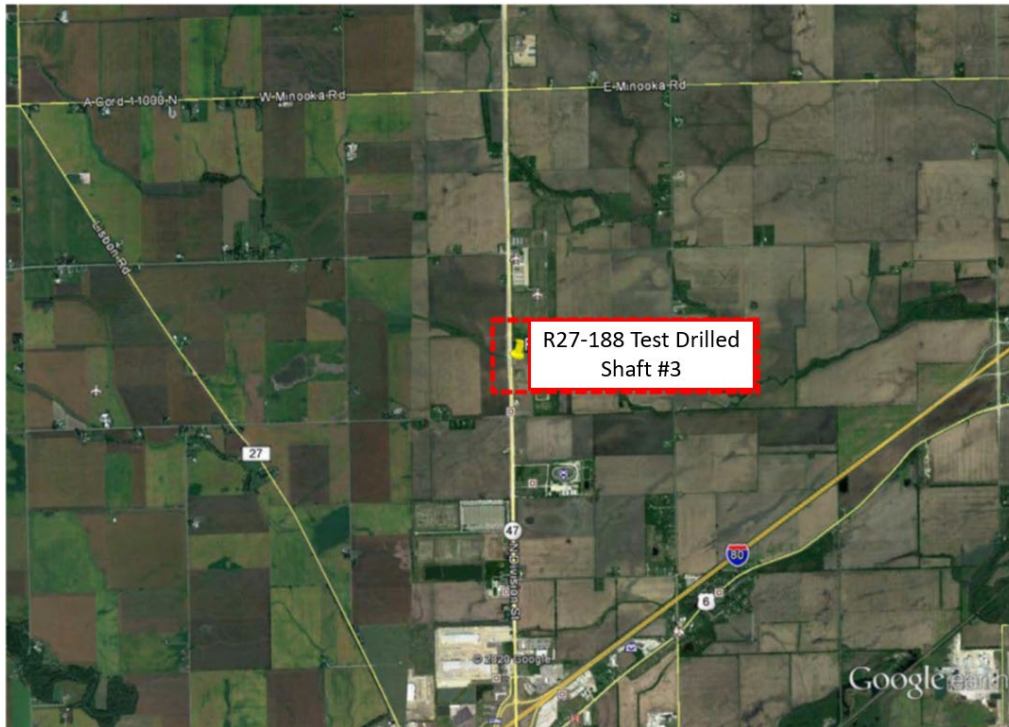


Figure 132. Photo. Location of test drilled shaft #3 0.3 miles North of Nelson Road in Grundy County, Illinois along IL-47.

Two soil borings were conducted using a hollow stem auger and a split-spoon sampler on February 21, 2020 and on March 3, 2020 as shown in Figure 133 and Figure 134, respectively. Figure 135 shows the plan view of the test drilled shaft #3 site location. The ground surface elevation is 563.01 ft. The second soil boring (see Figure 134) shows that the unconfined compression strength, and the water content range between 1 tsf to 5.7 tsf, and between 9% to 25%, respectively. Figure 134 also shows that the standard penetration test (SPT) blow count every twelve inches (N value) is 6, 6, 13, 24, 29, 30, 34, 30, 18, 14, 16, 35, and 34 and range from 6 and 35.

In the first soil boring (see Figure 133) the soil encountered is hard gray silty clay loam till from the ground surface up to a depth of approximately 34.5 ft. The boring was terminated when a weathered and fractured limestone layer was encountered at depth of approximately 34.5 ft. In the second soil boring (see Figure 134), the soil encountered is black silty clay loam to brown silty clay fill from the ground surface up to a depth of approximately 2.5 ft, stiff brown silty clay loam was encountered from approximately 2.5 ft to 7.5 ft, hard gray silty loam from approximately 7.5 ft to 10 ft, medium to

dense gray silty fine sand with thick silt layers from approximately 10 ft to 22 ft, hard gray clay with minor silt seams from approximately 22 ft to 29 ft, hard gray silty clay loam from approximately 29 ft to 35 ft, and gray limestone from approximately 35 ft to 36 ft below the ground surface, after which, the boring was terminate due to auger refusal.

Ground water was first encountered in the first soil boring (see Figure 133) was at elevation of approximately 545.0 ft (depth of 18 ft). Upon completion of the first soil boring, the ground water level was at elevation of approximately 559.0 ft (depth of 4 ft). For the second soil boring (see Figure 134), the depth of the ground water was first encountered at approximately 10 ft, which became approximately 8 ft deep upon completion of the soil boring.



Illinois Department of Transportation

Division of Highways

IDOT

SOIL BORING LOG

Page 1 of 1

Date 2/21/20

ROUTE IL 47

DESCRIPTION Drilled Shaft Test Site - IL 47, 0.3 miles North of Nelson Road in Grundy County

LOGGED BY Larry Myers

SECTION

LOCATION SW 1/4, SEC. 15, TWP. 34N, RNG. 7E, 3rd PM, Latitude 41.42026, Longitude -88.42261

COUNTY Grundy

DRILLING METHOD Hollow Stem Auger

HAMMER TYPE CME Automatic

STRUCT. NO.

Station

BORING NO. 01

Station

Offset

Ground Surface Elev. 563.01 ft

DEPTH

BL O W S

UCS Qu

MOIST

Surface Water Elev. ft

Stream Bed Elev. ft

Groundwater Elev.:

First Encounter 545.0 ft

Upon Completion 559.0 ft

After Hrs. ft

DEPTH

BL O W S

UCS Qu

MOIST

Augered Various Materials - Mainly Hard Gray Silty Clay Loam Till

Augered Various Materials - Mainly Hard Gray Silty Clay Loam Till (continued)

Limestone - Weathered & Fractured

End of Boring

528.51

The Unconfined Compressive Strength (UCS) Failure Mode is indicated by (B-Bulge, S-Shear, P-Penetrometer)

The SPT (N value) is the sum of the last two blow values in each sampling zone (AASHTO T206)

BBS, form 137 (Rev. 8-99)

Figure 133. Illustration. Soil Boring log #1 of test drilled shaft #3.

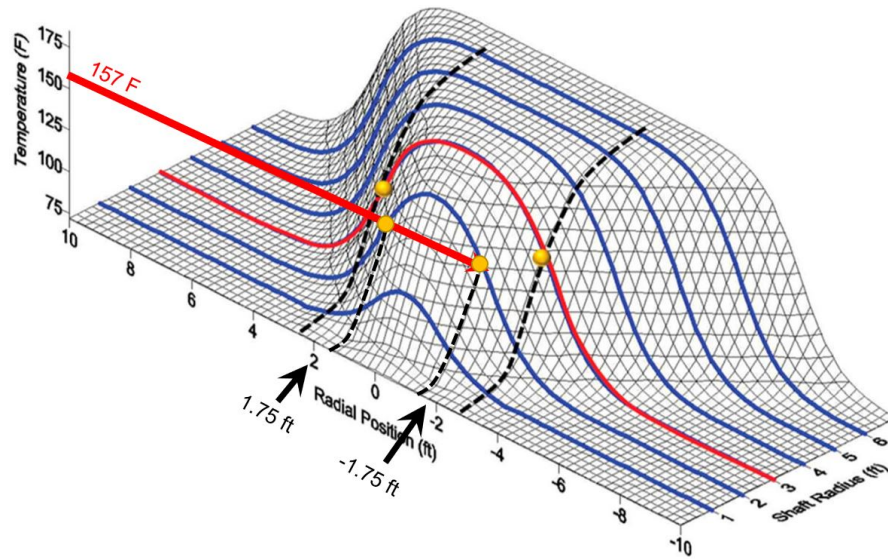


Figure 136. 3D graph. 3D temperature profile model for drilled shafts with black and red arrows added to show the temperature at the rebar cage of test drilled shaft #3 (after Johnson, 2016).

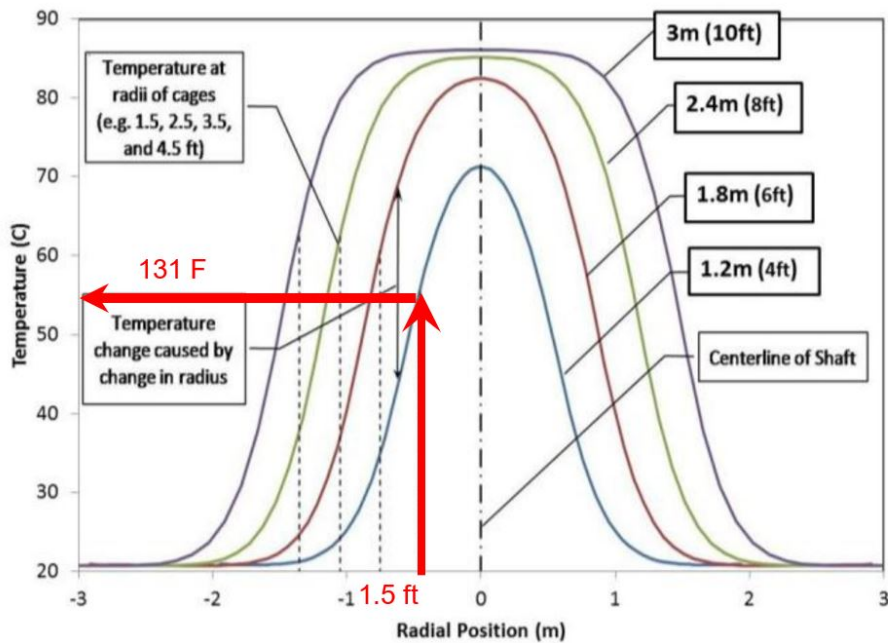


Figure 137. Graph. 2D temperature profile model for drilled shafts with red arrows added to show the temperature at the rebar cage of test drilled shaft #3 (after Mullins, 1997).

CONSULTANT A'S TIP RESULTS

Consultant A's results for test drilled shaft #3 include the thermal results that show the measured temperatures (Fahrenheit degrees) vs. depth (ft) for the odd, even, and all wires, respectively. For the odd wires, the measured temperatures are shown at 6h 25m (see Figure 138(a)), 13h 9m (see Figure 138(b)), 18h 55m (see Figure 139(a)), and 24h 11m (see Figure 139(b)) after placement of concrete.

Figure 140 (a) presents the estimated effective radius vs. depth for the odd wires, while a 3D interpretation of the tested drilled shaft is presented in Figure 140 (b).

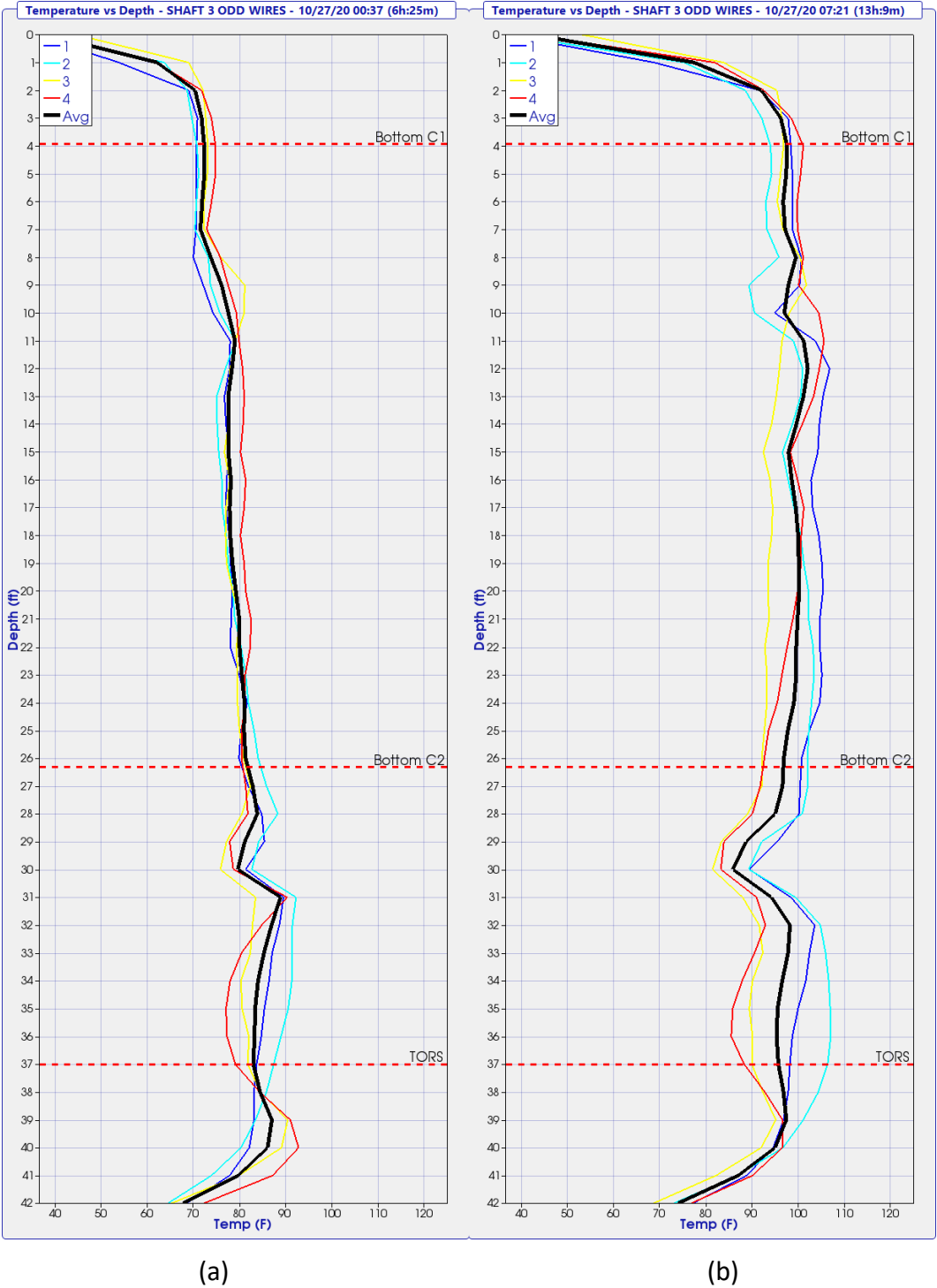


Figure 138. Graph. Temperature versus depth profile for the 4 odd wires in test drilled shaft #3: (a) at 6h 25m, and (b) at 13h 9m after concrete placement.

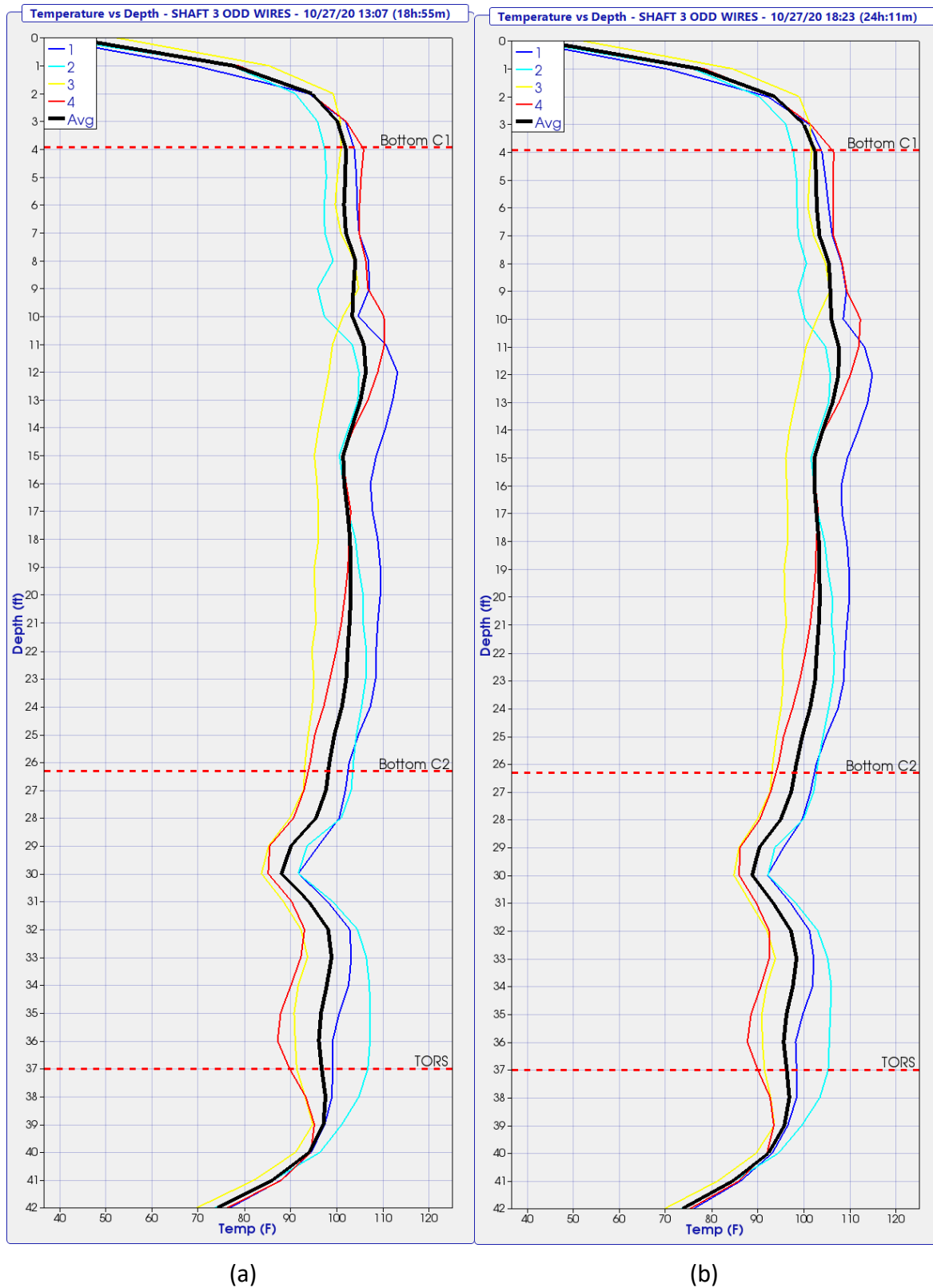
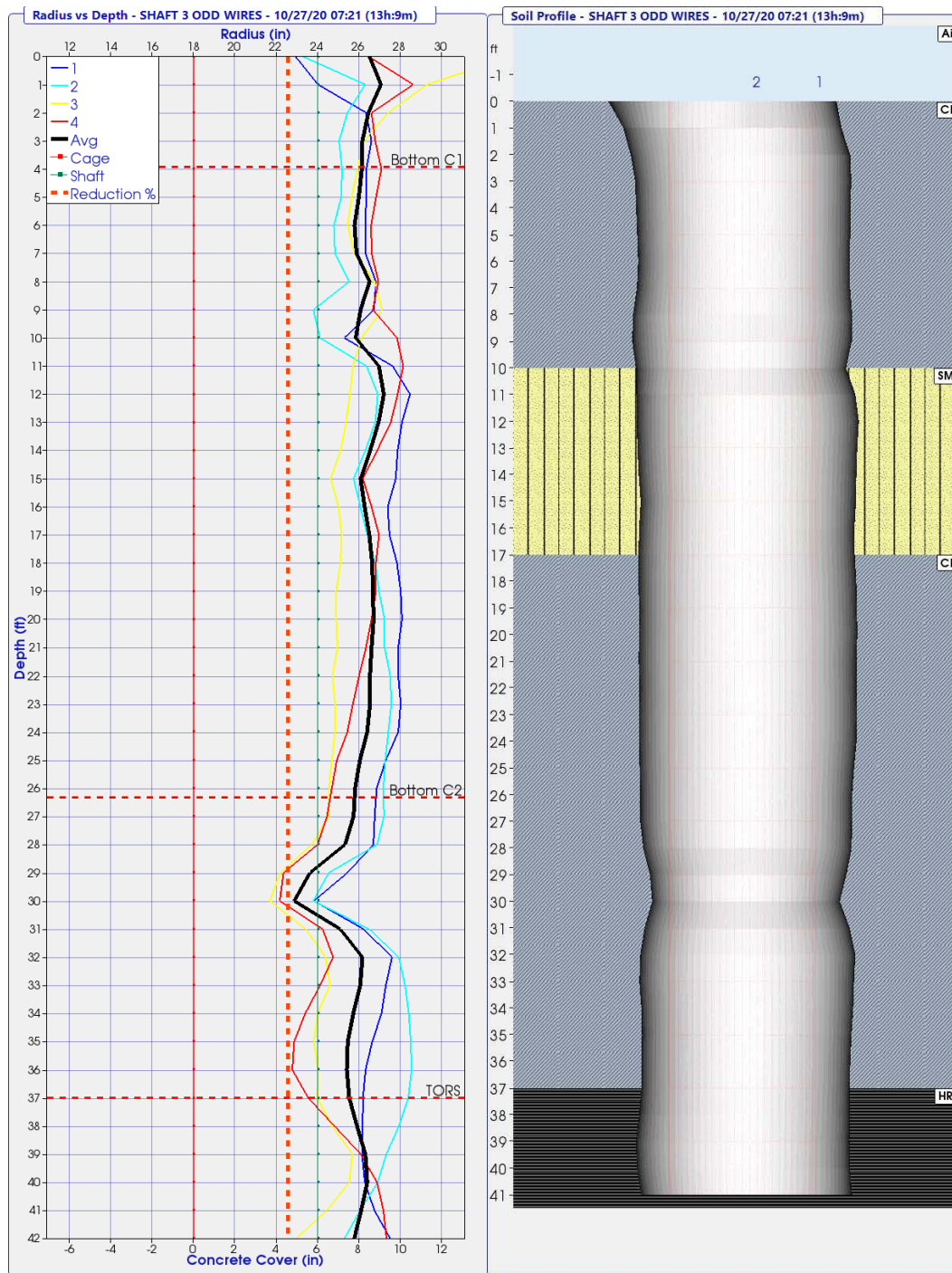


Figure 139. Graph. Temperature versus depth profile for the 4 odd wires in test drilled shaft #3: (a) at 18h 55m, and (b) at 24h 11m (peak) after concrete placement.



(a)

(b)

Figure 140. Graph. (a) radius versus depth and illustration. (b) 3D rendering for the 4 odd wires in test drilled shaft #3.

For the even wires, the measured temperatures are shown at 6h 32m (see Figure 141(a)), 12h 47m (see Figure 141(b)), 18h 33m (see Figure 142(a)), and 23h 24m (see Figure 142(b)) after placement of

concrete. Figure 143 (a) presents the estimated effective radius vs. depth for the even wires, while a 3-D interpretation of the tested drilled shaft is presented in Figure 143 (b).

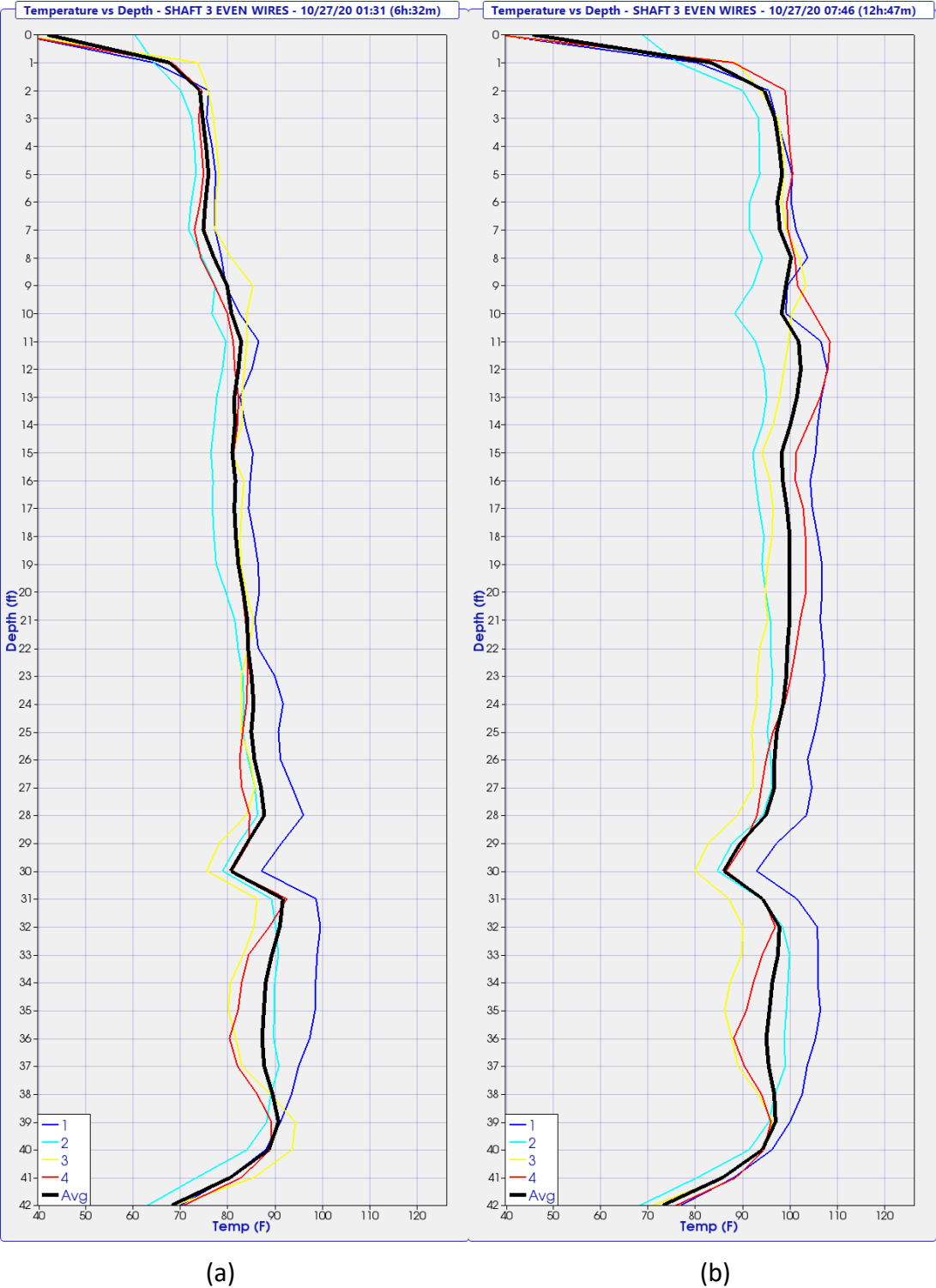


Figure 141. Graph. Temperature versus depth profile for the 4 even wires in test drilled shaft #3: (a) at 6h 32m, and (b) at 12h 47m after concrete placement.

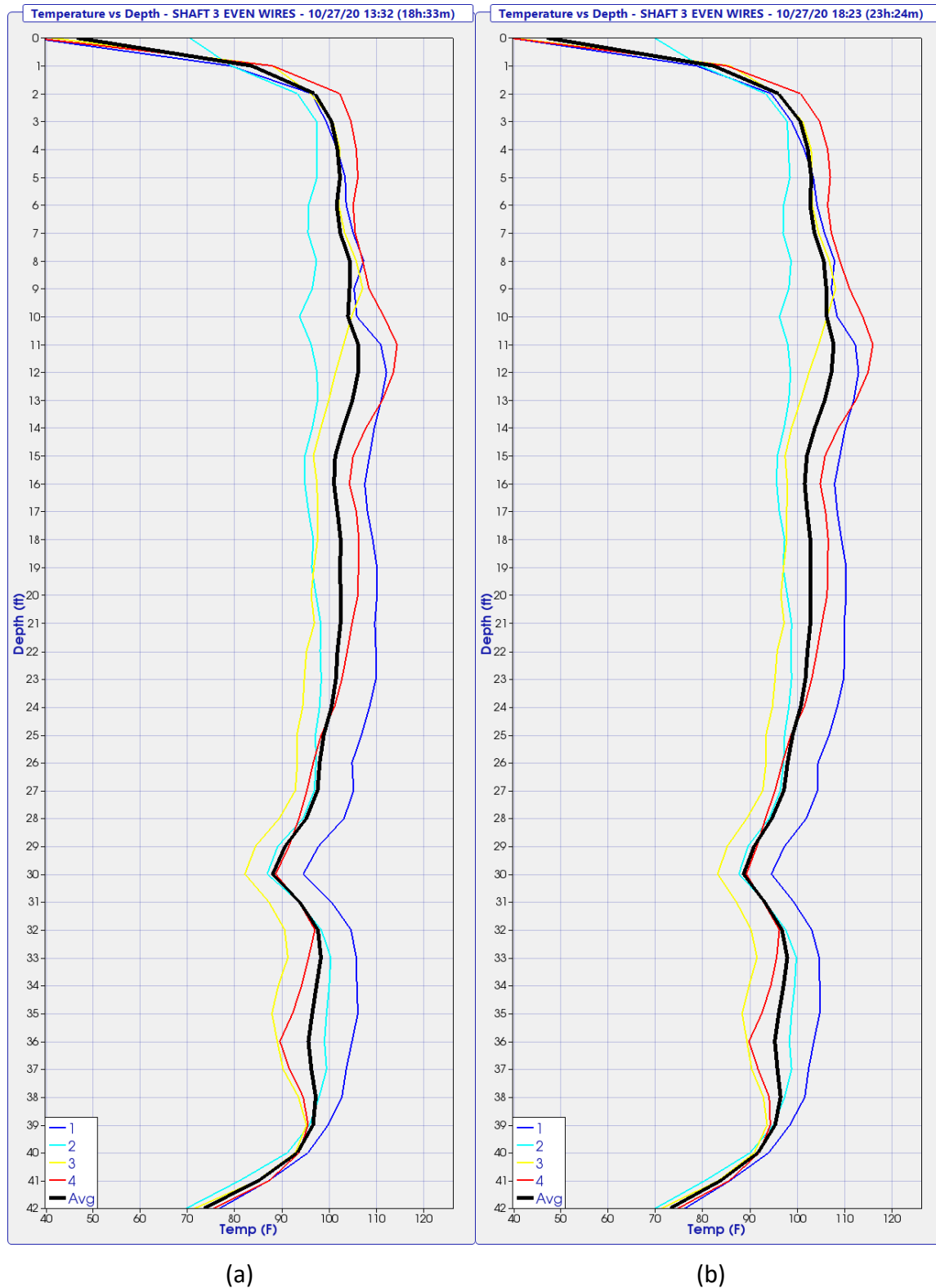


Figure 142. Graph. Temperature versus depth profile for the 4 even wires in test drilled shaft #3: (a) at 18h 33m, and (b) at 23h 24m (peak) after concrete placement.

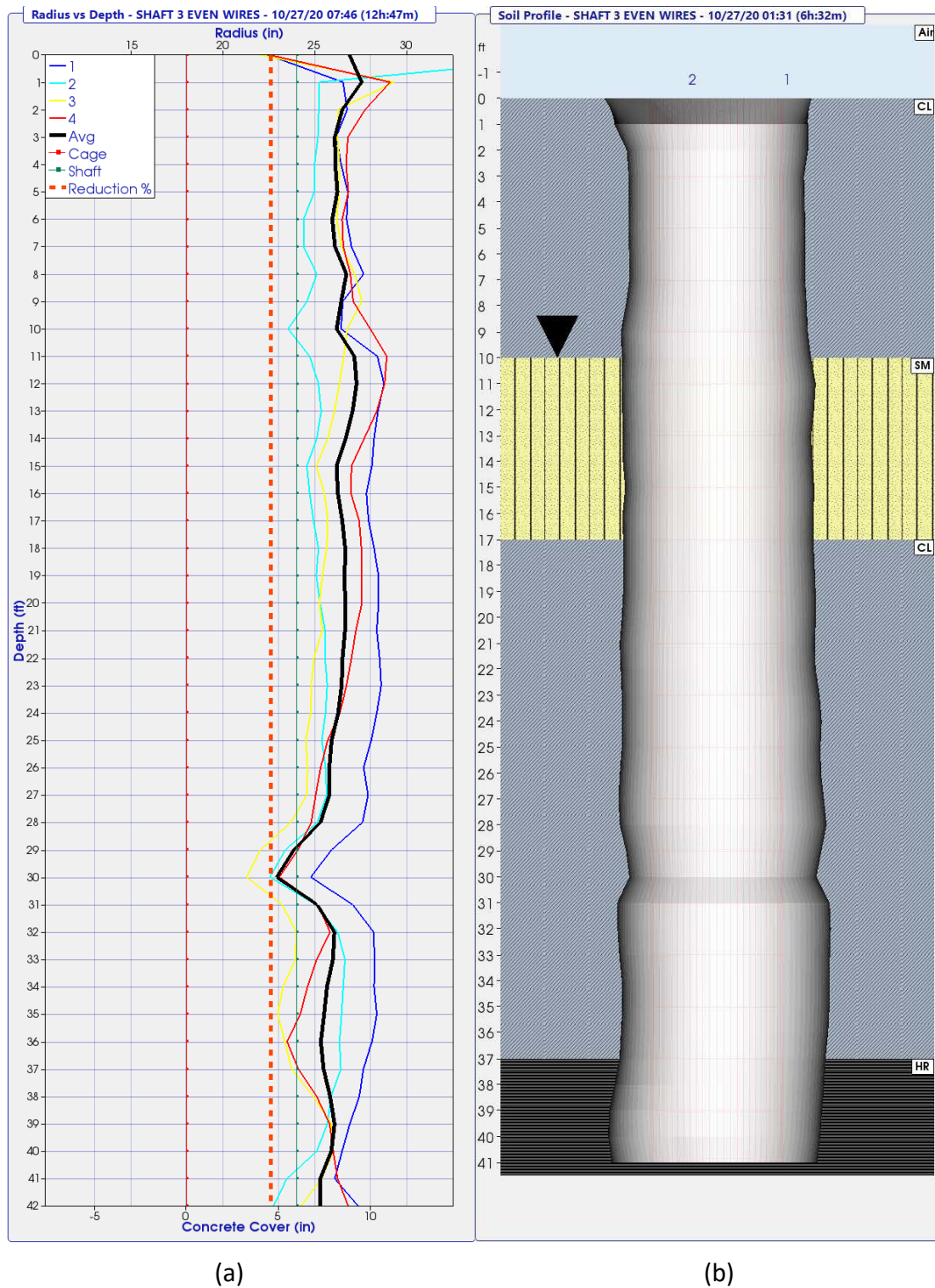


Figure 143. Graph. (a) radius versus depth and Illustration. (b) 3D rendering for the 4 even wires in test drilled shaft #3.

For all the wires, the measured temperatures are shown at 8h 38m (see Figure 144(a)), 13h 5m (see Figure 144(b)), 16h 7m (see Figure 145(a)), and 23h 24m (see Figure 145(b)) after placement of concrete. Figure 146 (a) presents the estimated effective radius vs. depth for all the wires, while a 3-D interpretation of the tested drilled shaft is presented in Figure 146 (b).

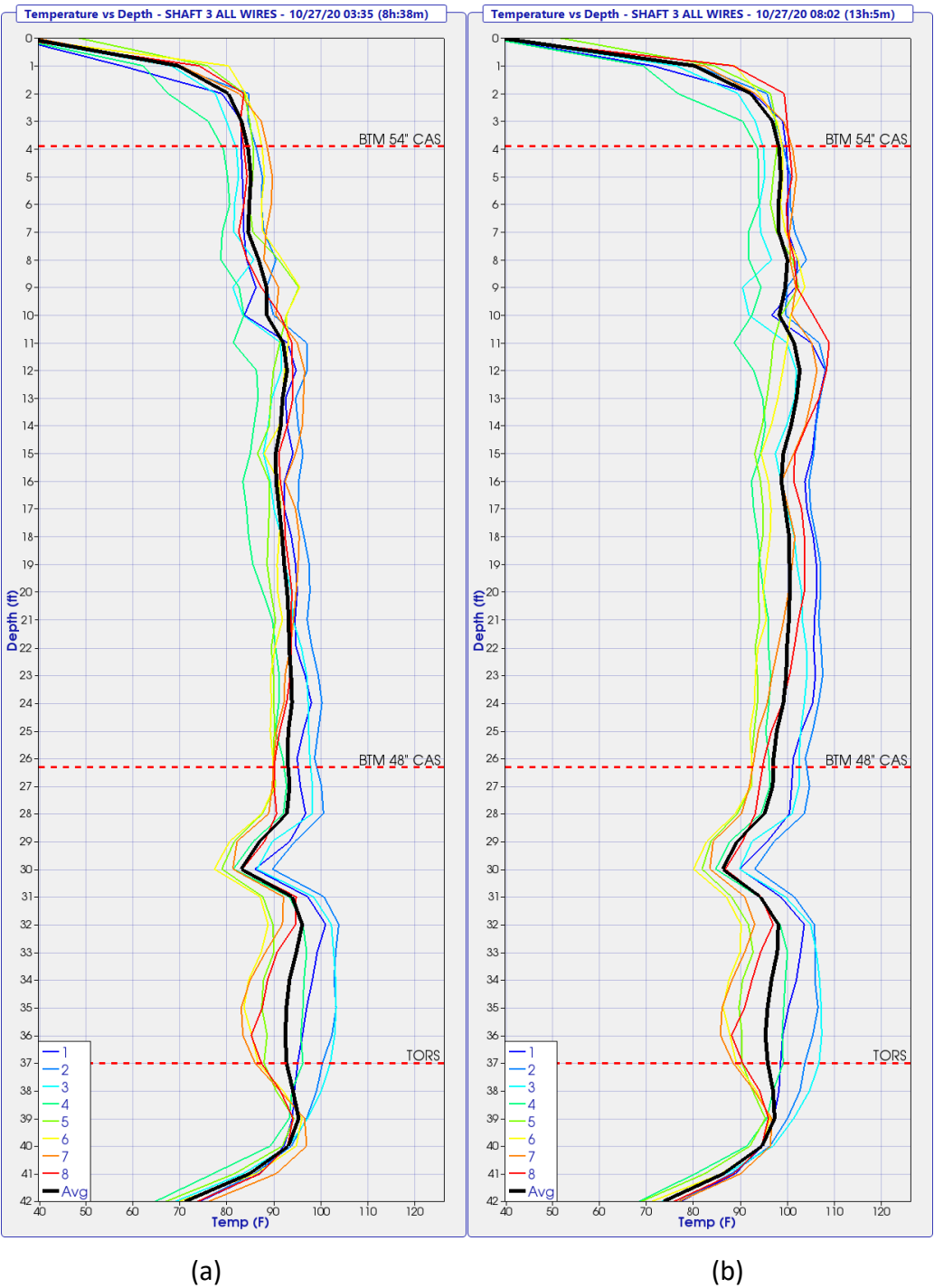


Figure 144. Graph. Temperature versus depth profile for all the 8 wires in test drilled shaft #3: (a) at 8h 38m, and (b) at 13h 5m after concrete placement.

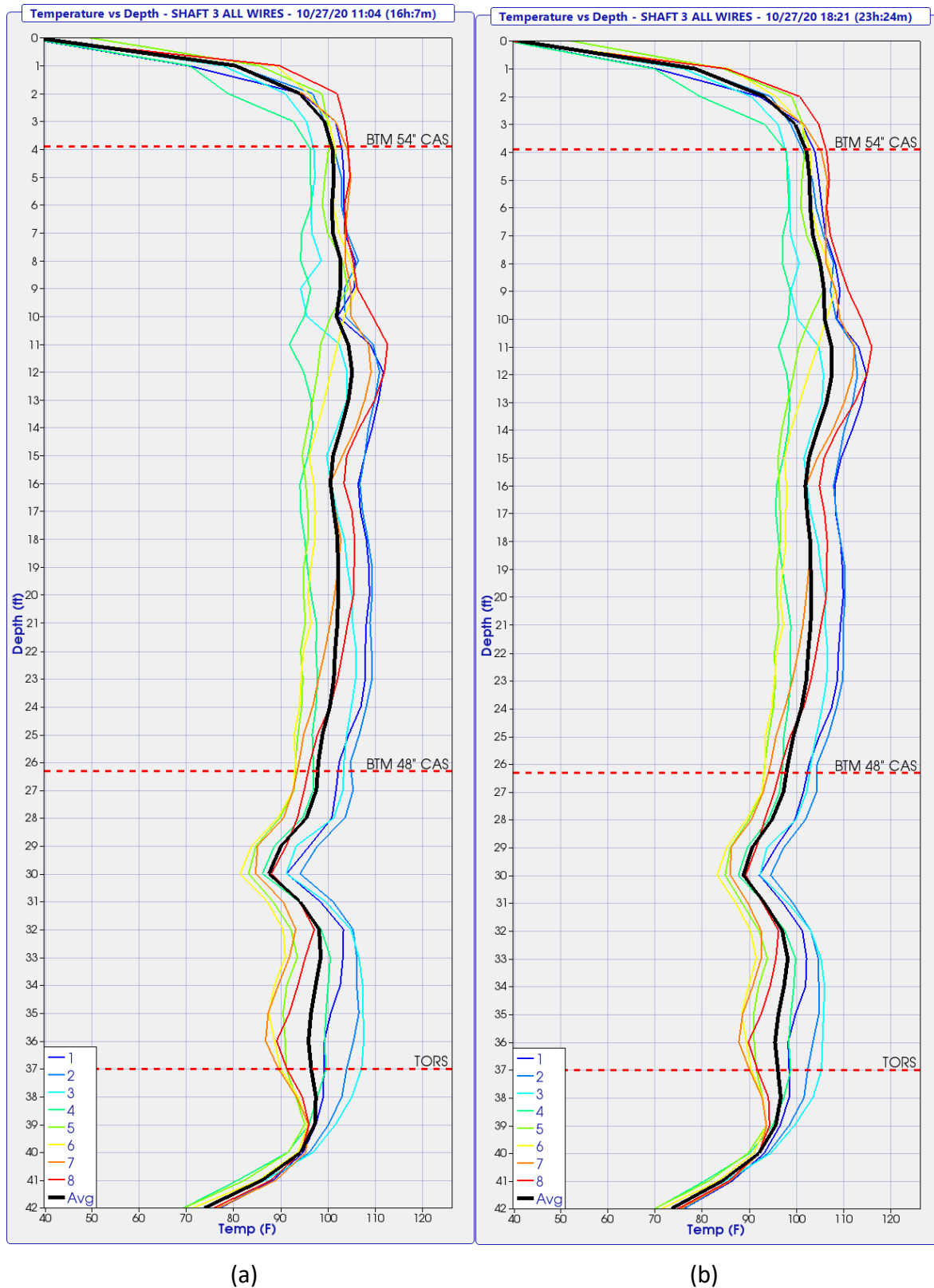


Figure 145. Graph. Temperature versus depth profile for all the 8 wires in test drilled shaft #3: (a) at 16h 7m, and (b) at 23h 24m (peak) after concrete placement.

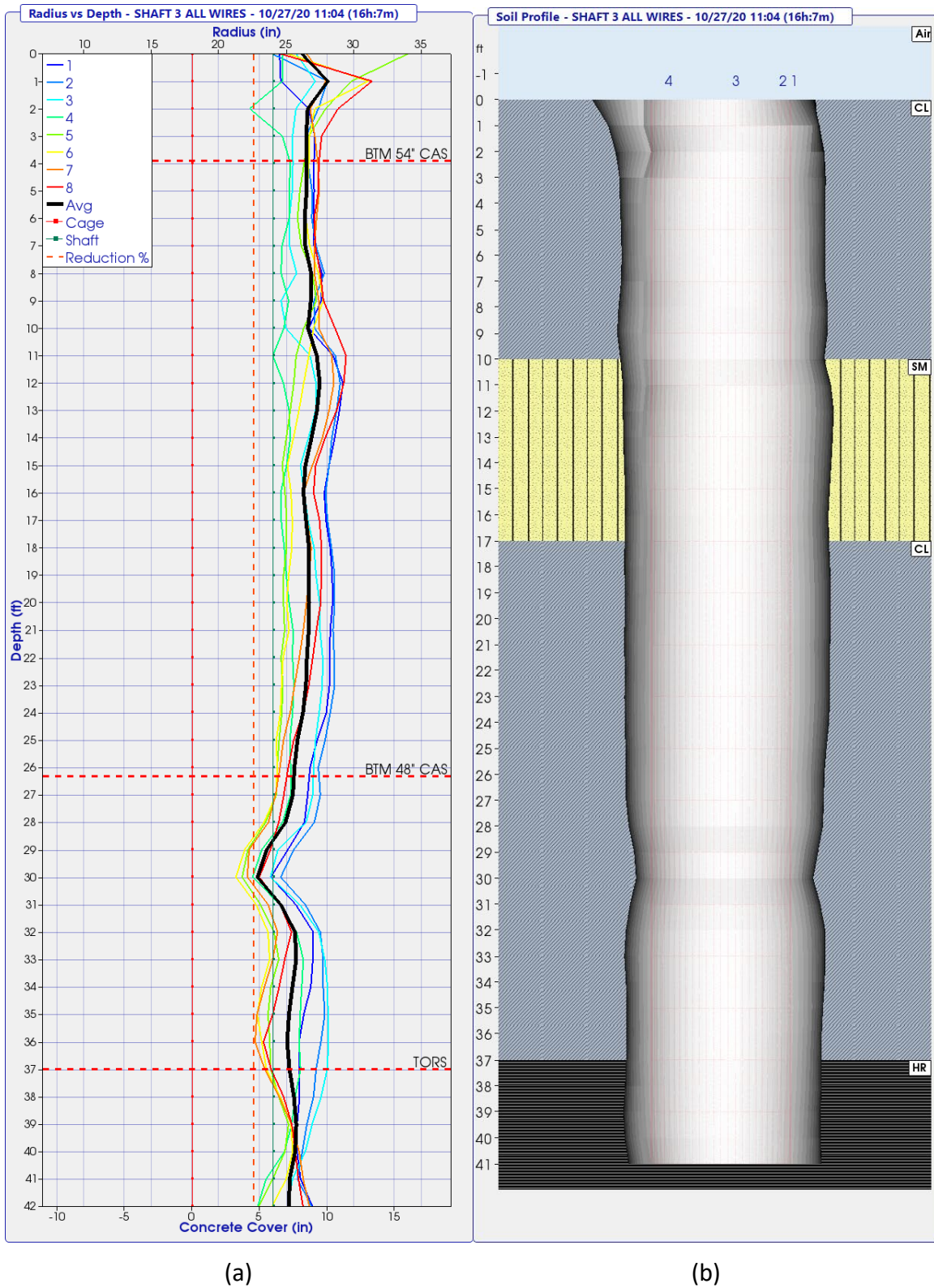


Figure 146. Graph. (a) radius versus depth and Illustration. (b) 3D rendering for all the 8 wires in test drilled shaft #3.

UIUC's Interpretation of TIP Results

Figure 147 shows the 3D rendering for test drilled shaft #3 with added arrows showing the defect locations for the odd wires. Figure 148 shows the 3D rendering for test drilled shaft #3 with added arrows showing the defect locations for the even wires. Figure 149 shows the 3D rendering for test drilled shaft #3 with added arrows showing the defect locations for all the wires. The bold red dashed line in Figure 147, Figure 148, and Figure 149 shows the theoretical radius of the drilled shaft.

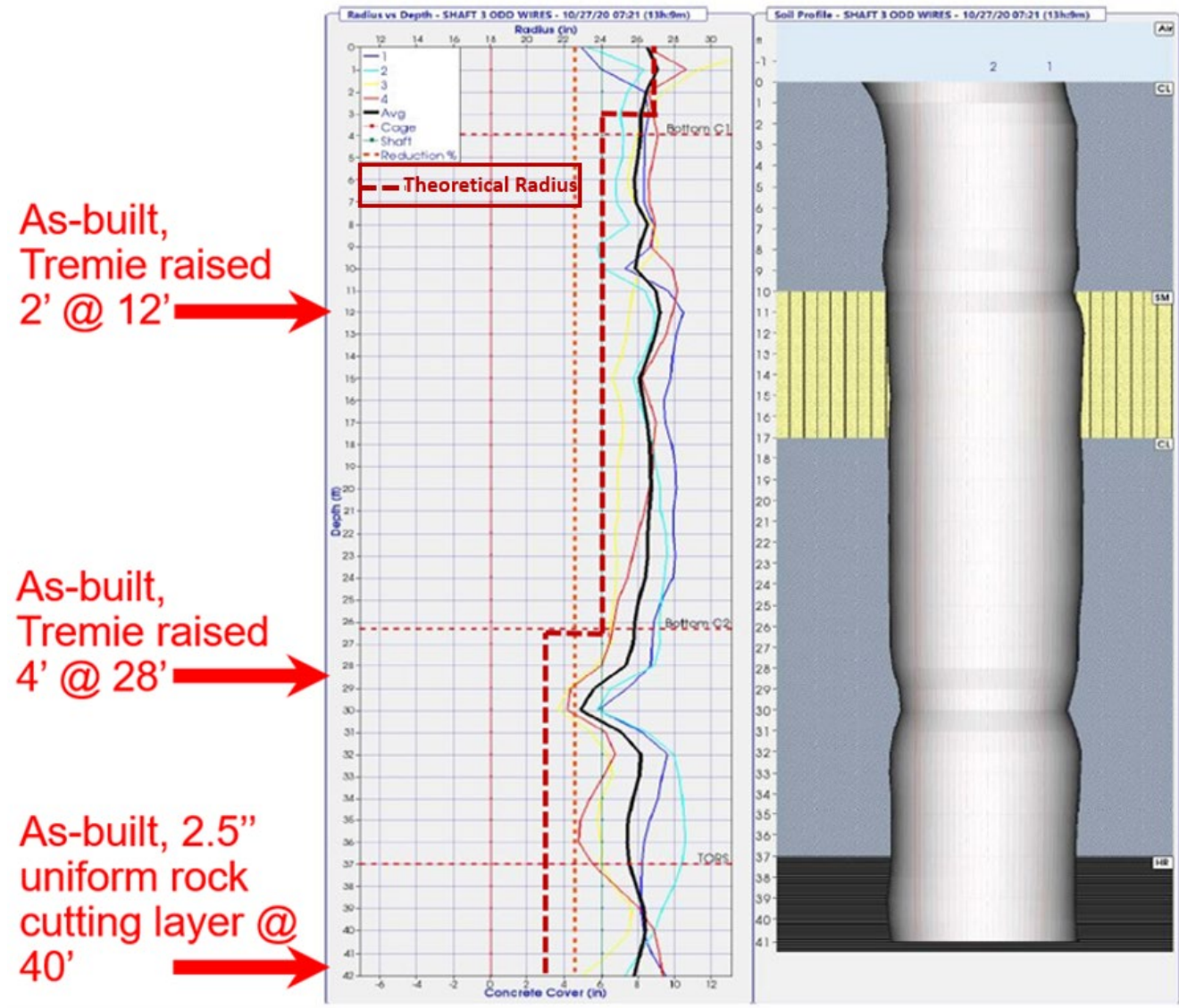


Figure 147. Illustration. 3D rendering for test drilled shaft #3 (odd wires).

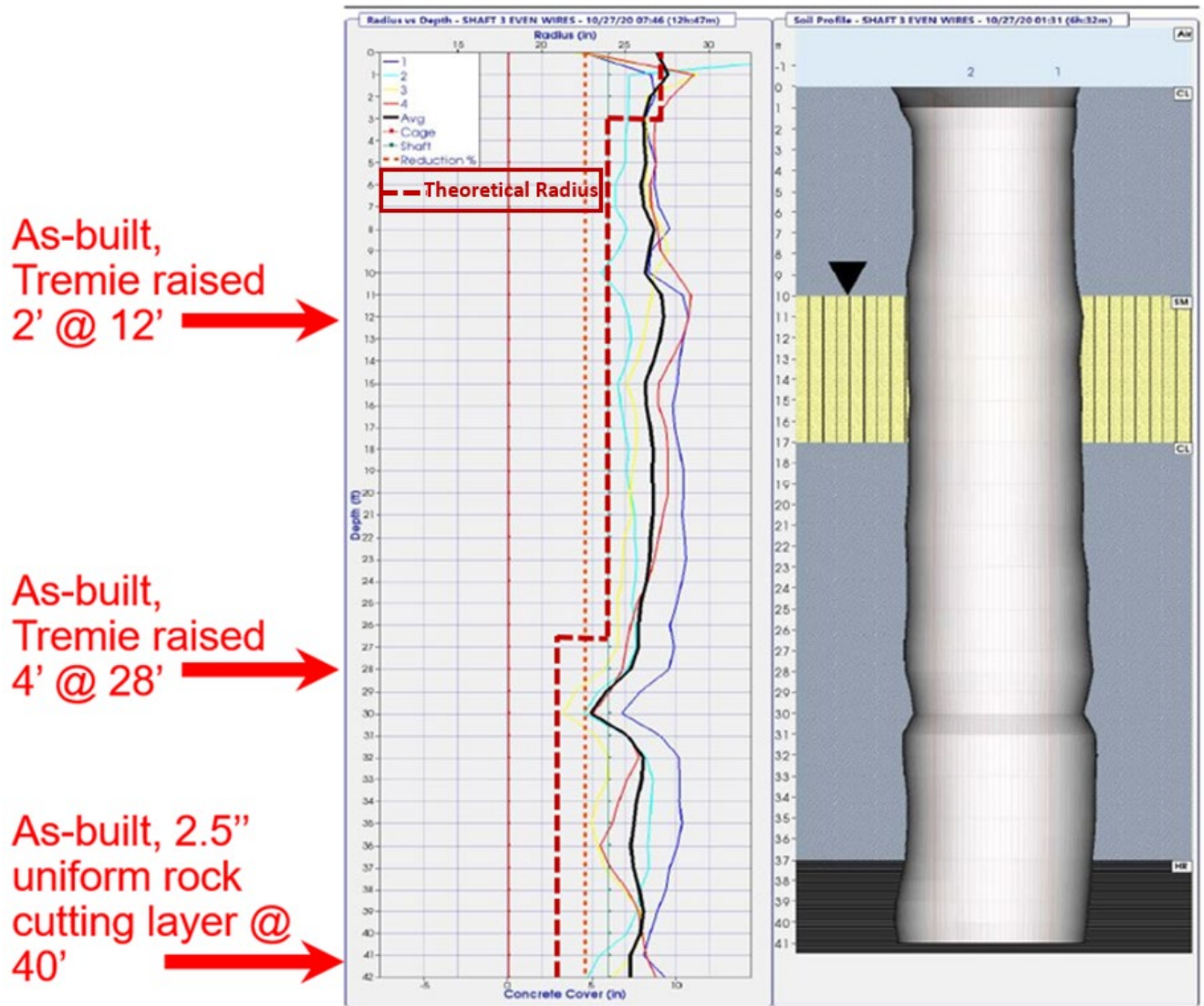


Figure 148. Illustration. 3D rendering for test drilled shaft #3 (even wires).

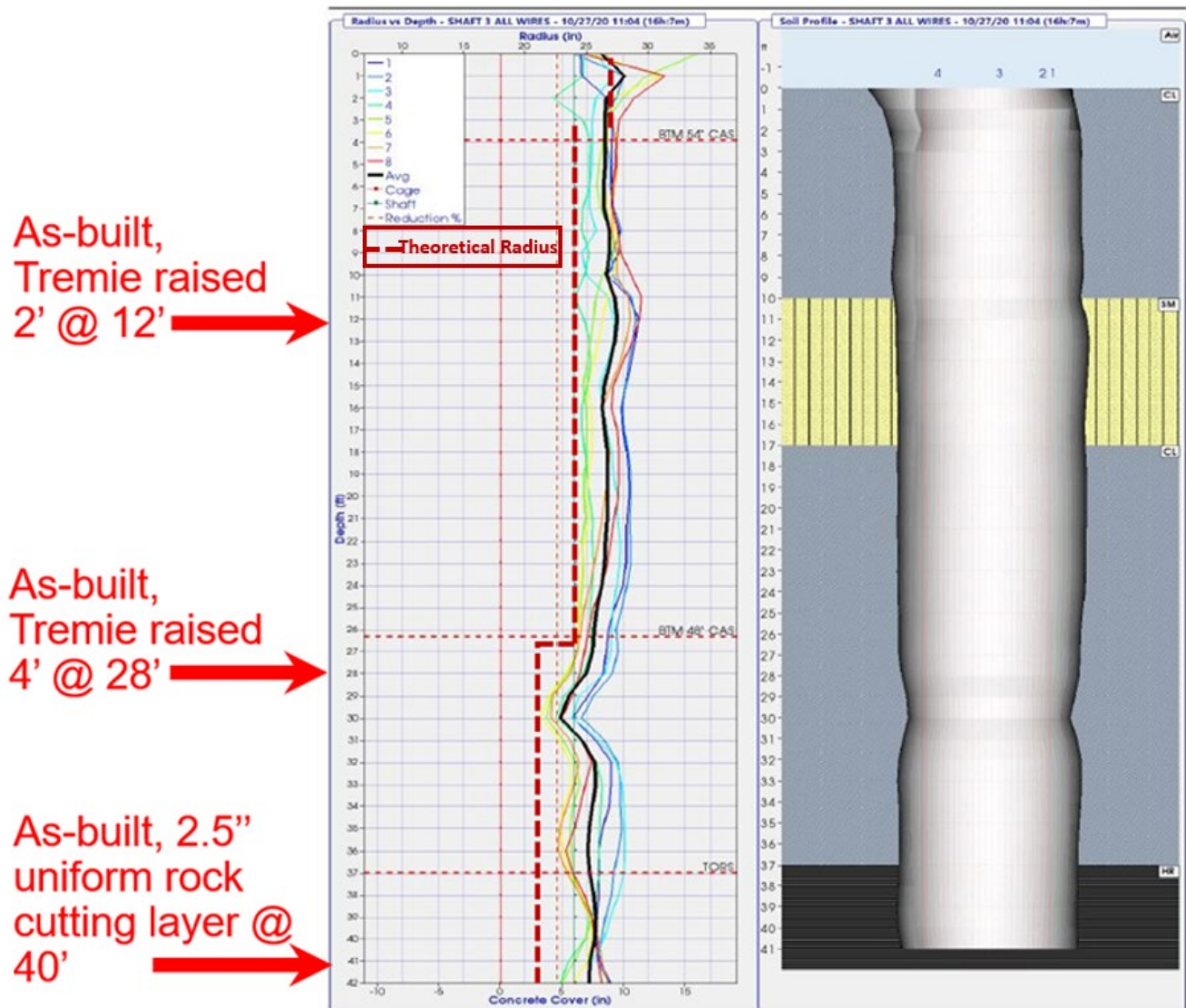


Figure 149. Illustration. 3D rendering for test drilled shaft #3 (all wires).

An interpretation of the measured temperature profiles with depth for all the thermal wires was also conducted by the research team. The temperatures profiles at the peak, and one-half time to peak temperatures are considered in the analysis described below. Boeckmann and Loehr (2018) show that the analysis of TIP data is more sensitive to defects at times corresponding to roughly one-half the time to peak temperature and yields more accurate assessment of potential defects. Figure 150 shows the temperature versus depth profile for the four odd wires in test drilled shaft #3 at peak temperature and one-half the time to peak temperature.

The temperature profiles shown in Figure 150(a) and Figure 150(b) are the same as those shown in Figure 138(b) and Figure 139(b) near the one-half the time to peak temperature and at peak temperatures, respectively. However, Figure 150 shows the defect locations. Figure 151 shows the temperature versus depth profile for the four even wires in test drilled shaft #3 at peak temperature and one-half the time to peak temperature. The temperature profiles shown of the even wires in

Figure 151(a) and Figure 151(b) are the same as those shown in Figure 141(b) and Figure 142(b) near the time of one-half the time to peak temperature and at peak temperatures, respectively. However, the even wires in Figure 151 shows the defect locations. Figure 152 shows the temperature versus depth profile for all the 8 wires in test drilled shaft #3 at peak temperature and one-half the time to peak temperature. Figure 153 shows the temperature profiles for test drilled shaft #3 at one-half the time to peak temperature for the odd, even, and all wires.

Similar to test drilled shaft #1 and #2, when comparing the temperatures profiles at one-half the time to peak to those at the peak temperature, more deviation between the profiles and clearer observation of temperature reductions were observed at defects for the figures at one-half the time to peak temperatures. For example, the defects around 10 ft and around 30 ft can be more evident at one-half the time to peak temperatures profiles in Figure 150, Figure 151, and Figure 152 than at the peak temperatures profiles, because the reduction in temperature is higher at the one-half the time to peak temperatures. This is the reason why in Figure 153, only the temperatures profiles at one-half the time to peak temperature are shown for the odd, even, and all the wires. Figure 153 shows a clear reduction in temperature around 10 ft and 30 ft.

All wires in all the figures show a clear reduction in temperature around 30 ft. The reduction in temperature is also obvious at around 10 ft by most of the wires in all the figures but not as clear and large reduction as the one at 30 ft. This might be attributed to the fact that the height of the tremie pipe raise at 28 ft is 4 ft which is larger than that at 12 ft which is only 2 ft. Furthermore, it seems that there is an offset by 2 ft between the location of these two defects and where it is detected by TIP testing. For example, for the first defect at 12 ft the results show a reduction at 10 ft and for the second defect at 28 ft, the results show a reduction in the temperature at 30 ft. The last defect at the bottom of the test shaft couldn't be detected due to the rolloff of the temperature profile at the base of the test shaft. Similar to test drilled shaft #2, there was no planned rebar cage shift, however this does not mean one did not occur during construction. Since Consultant A concluded a rebar cage shift occurred, the research team felt it was appropriate to further investigate it. The odd wires in Figure 150 shows a clear shifting of the light blue (wire #2) and red (wire #4) colored wires at about 19 ft which are opposite to each other as shown on the wires sketch on the same figure. This can also be seen by the shifting of the even wires in Figure 151 at about 25 ft by the light blue (wire #2) and red (wire #4) colored wires which are also opposite to each other. The cross section of the test drilled shaft #3 changing from 48 in. to 42 in. at 26.5 ft and the overall oversize of the effective radius were not detected by the research team when using the odd, even, or all the wires. It is important to note that using double the required number of thermal wires in TIP testing didn't provide almost any additional insights to the integrity of the shaft. Therefore, there is no need to use more than one thermal wire per foot of shaft diameter (see Appendix F for IDOT specifications).

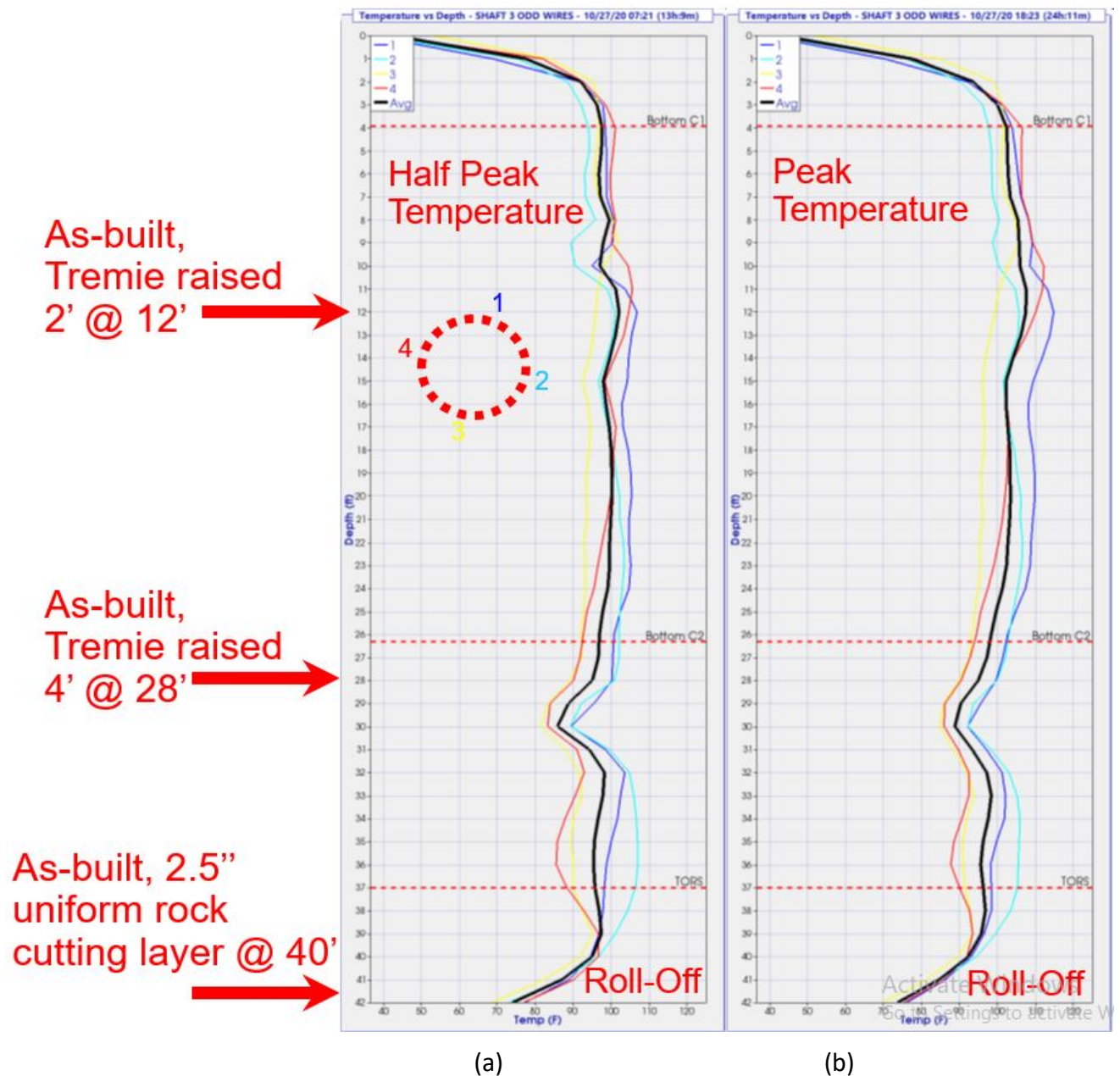


Figure 150. Graph. Temperature versus depth profile for the 4 odd wires in test drilled shaft #3: (a) at one-half the time to peak temperature, and (b) at peak with red arrows showing the location of installed defects.

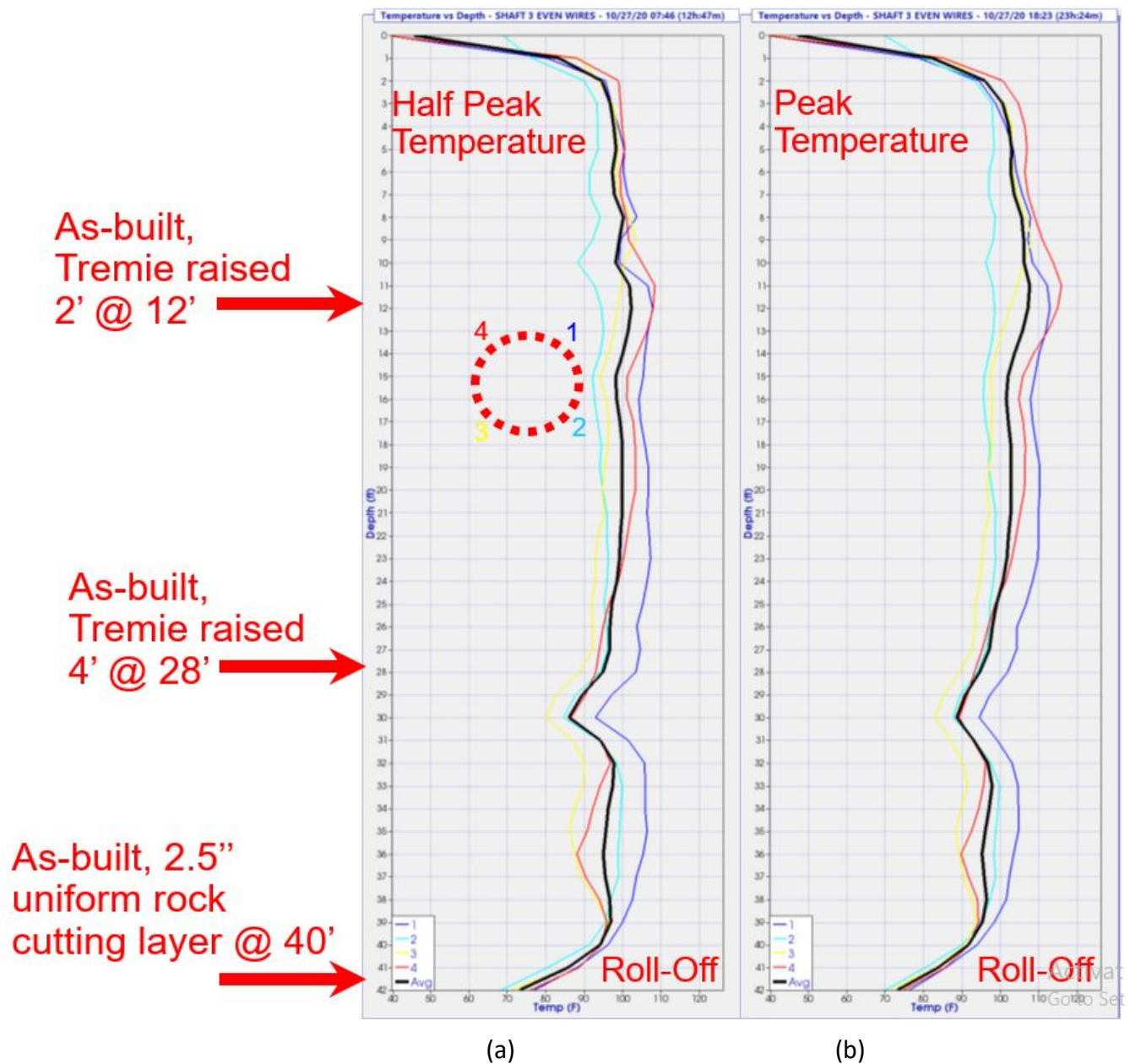


Figure 151. Graph. Temperature versus depth profile for the 4 even wires in test drilled shaft #3; (a) at one-half the time to peak temperature, and (b) at peak temperature with red arrows showing the location of installed defects.

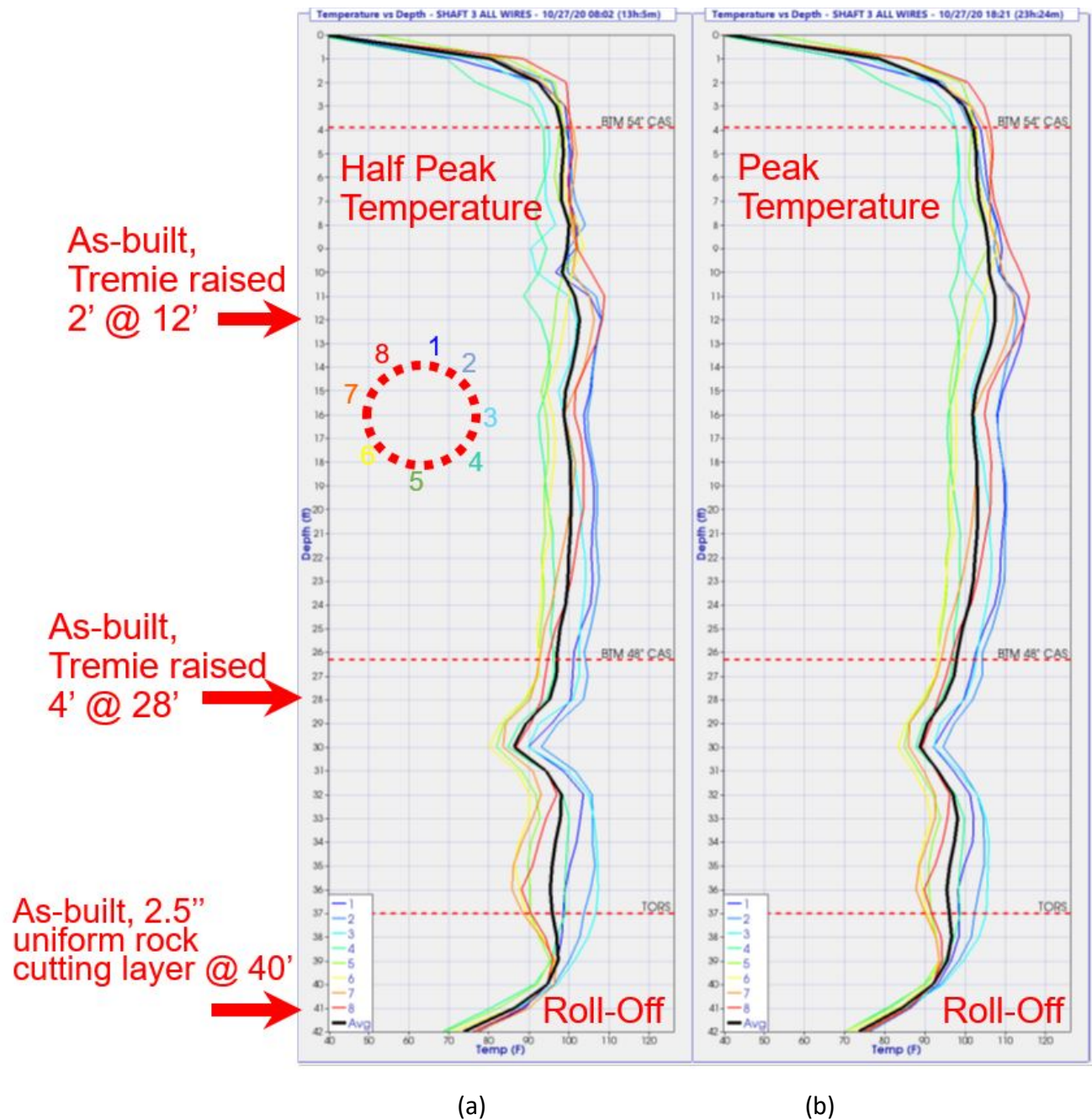


Figure 152. Graph. Temperature versus depth profile for all the 8 wires in test drilled shaft #3; (a) at one-half the time to peak temperature, and (b) at peak temperature with red arrows showing the location of installed defects.

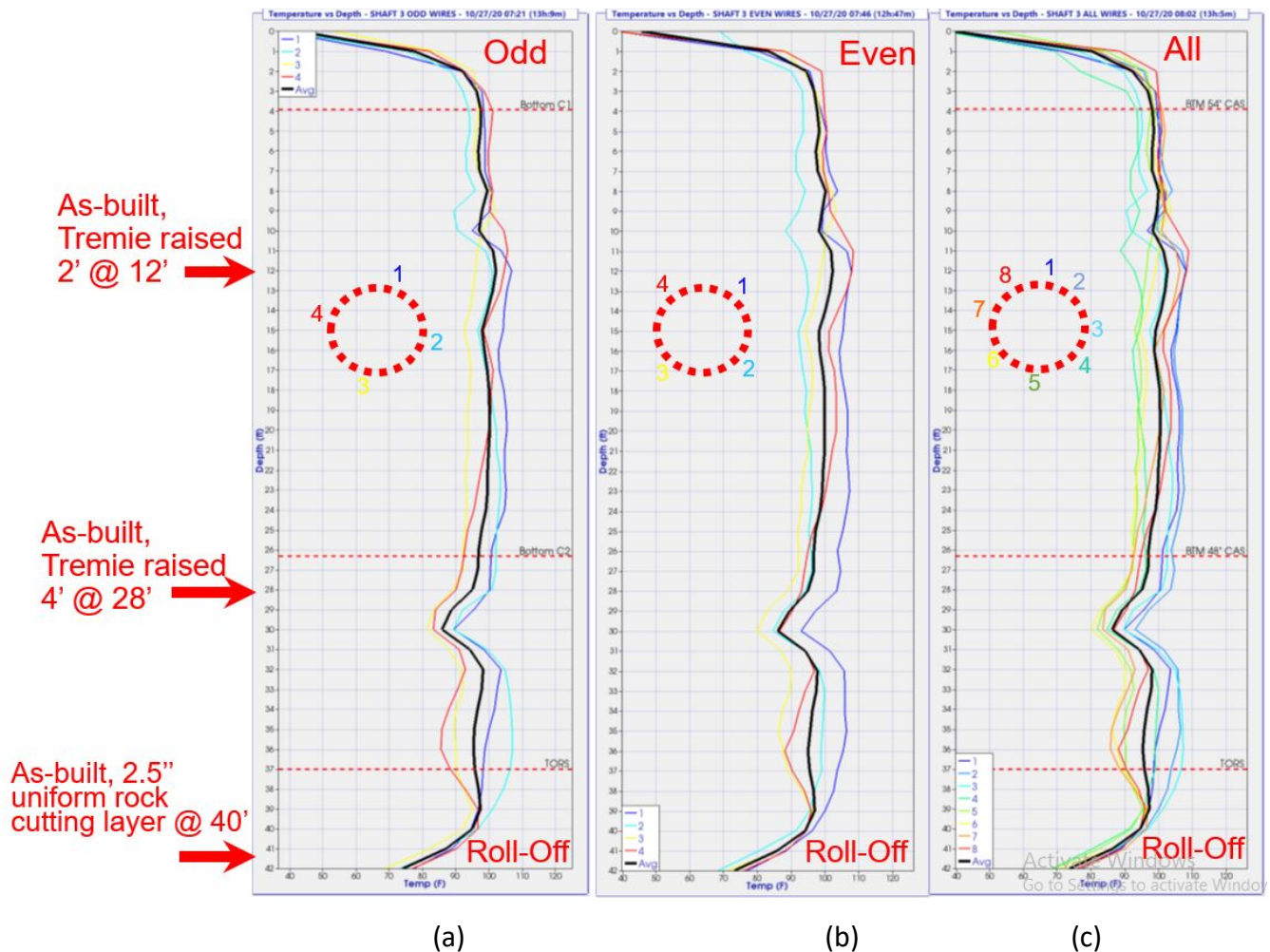


Figure 153. Graph. One-half time to peak temperature profiles for test drilled shaft #3 for: (a) odd wires, (b) even wires, and (c) all wires.

CORING OF TEST SHAFT #3

Figure 154 shows a sketch of test drilled shaft #3 with the relative locations of the first core (core #1) and the second core (core #2). Figure 155 shows the cores obtained from the first coring of test drilled shaft #3 showing the start and end of observed defect between depth of 28 ft 6 in. and 29 ft 8 in. Figure 156 show a photograph of a joint observed at a depth of 11 ft 9 in. from the second coring of test drilled shaft #3. Figure 157 shows the cores obtained from the second coring of test drilled shaft #3 showing the start and end of observed defect between depth of 28 ft 7 in. and 29 ft 7 in. Figure 158 shows a close-up photograph of the start and end of the defect observed between depth of 28 ft 7 in. and 29 ft 7 in from the second coring. This defect was observed in the field as gravel and/or broken up concrete with a length of 12 in.

Figure 159 shows the cores obtained from the second coring of test drilled shaft #3 showing the start and end of the observed defect between 41 ft 11 in. and 42 ft 6 in in addition to the end of coring at 43'1" that is believed to be in the soil underlying the shaft. Figure 160 shows close-up photographs of

the start and end of the defect observed between depth of 41 ft 11 in. and 42 ft 6 in. This defect was observed in the field as clay with some broken up concrete having a length of 7 in.

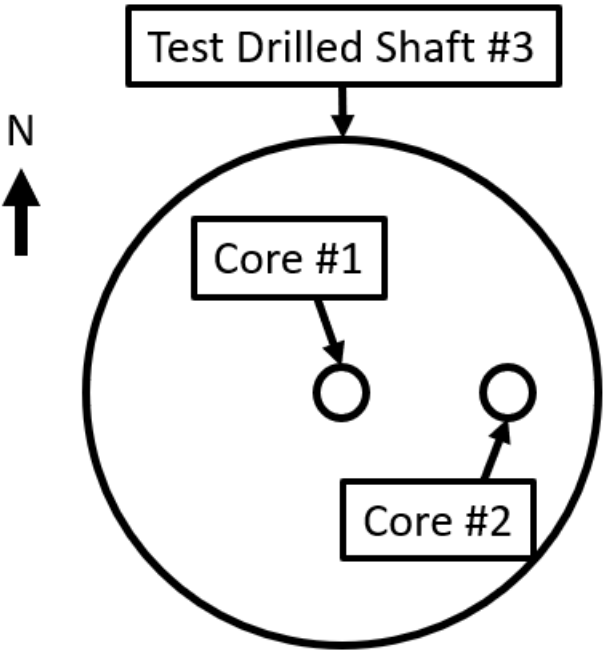


Figure 154. Sketch. Sketch showing the first core (core #1) and the second core (core #2) locations in test drilled shaft #3.



Figure 155. Photo. Photograph showing the start of defect at 28 ft 6 in. depth and end of defect at 29 ft 8 in. depth from core #1 of test drilled shaft #3.

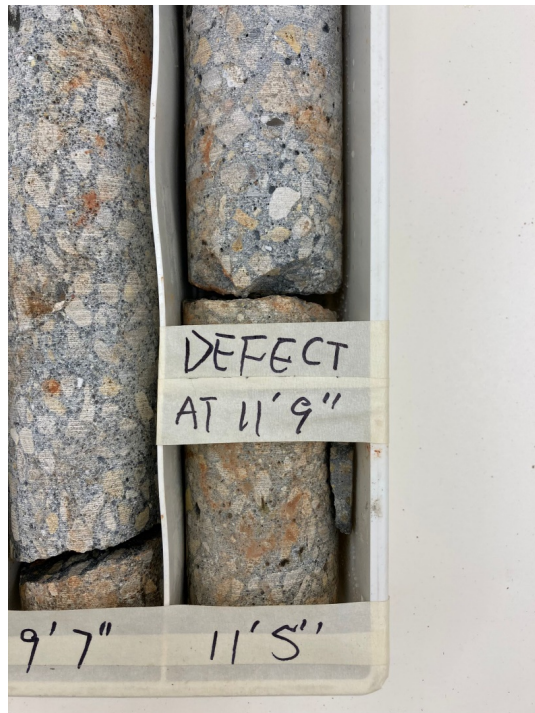


Figure 156. Photo. Photograph showing a core obtained from core #2 of test drilled shaft #3 showing a joint at a depth of 11 ft 9 in.



Figure 157. Photo. Photograph showing a core obtained from core #2 of test drilled shaft #3 showing the start and end of an observed defect between depths of 28 ft 7 in. and 29 ft 1 in.



(a)



(b)

Figure 158. Photo. Close-up photographs showing: (a) start of defect at 28 ft 7 in. and (b) end of defect at 29 ft 7 in. from core #2 of test drilled shaft #3.



Figure 159. Photo. Photograph showing a core obtained from test shaft #3 showing the start and end of observed defect between a depth of 41 ft 11 in. and 42 ft 6 in from core #2 of test drilled shaft #3.



(a)

(b)

Figure 160. Photo. A close-up photograph showing the: (a) start of defect at 41 ft 11 in. depth and (b) end of defect at 42 ft 6 in. depth from core #2 of test drilled shaft #3.

INSTALLATION RECORDS

Figure 161 shows a sketch of the TIP wires configuration with wire-wire distances, the serial number for each wire, and general drilled shaft information, while Table 39, Table 40, and Table 41 show the actual distance measurements that were taken by the research team between wires at the bottom of the cage for all wires, even numbered wires, and odd numbered wires, respectively.

THERMAL FIELD LOG

Project R27-188

Date Placed: 10/26/2020

Pier No. _____

Shaft No. 3

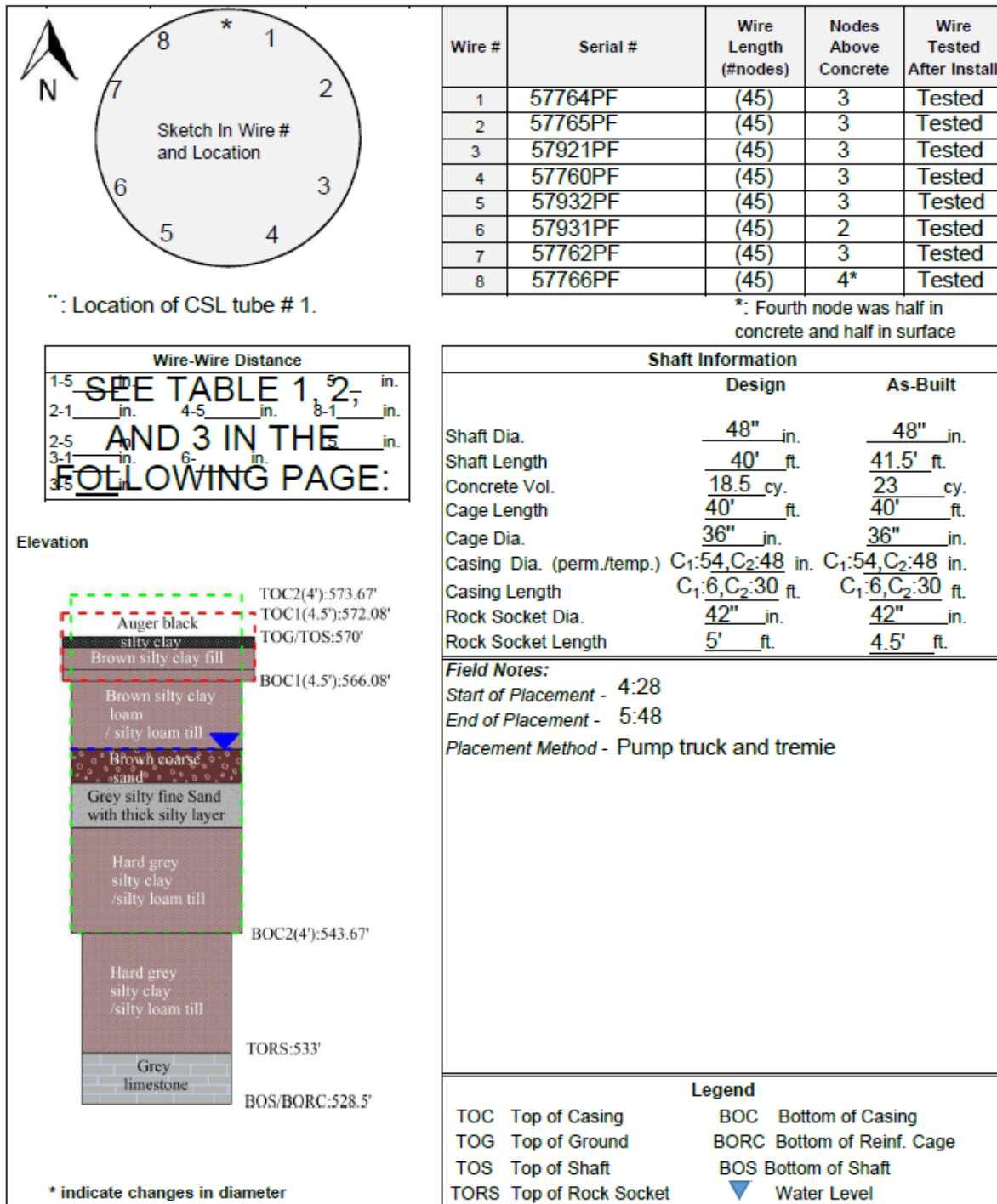


Figure 161. Illustration. TIP installation log for test drilled shaft #3.

Table 39. All Wire-Wire Distances for the 8 TIP Wires

Wire Number	Wire Number	Distance (inch)	Wire Number	Wire Number	Distance (inch)
1	2	9.50	3	5	27.75
1	3	22.00	3	6	31.50
1	4	32.50	3	7	32.75
1	5	33.50	3	8	31.00
1	6	30.50	4	5	14.50
1	7	22.00	4	6	22.00
1	8	14.75	4	7	30.50
2	3	14.00	4	8	33.75
2	4	28.50	5	6	8.75
2	5	33.00	5	7	21.25
2	6	32.75	5	8	27.50
2	7	27.00	6	7	14.25
2	8	21.50	6	8	22.00
3	4	17.75	7	8	9.00

Table 40. Even-Even Wire-Wire Distances for the 8 TIP Wires

Wire Number	Wire Number	Distance (inch)
2	4	28.50
2	6	32.75
2	8	21.50
4	6	22.00
4	8	33.75
6	8	22.00

Table 41. Odd-Odd Wire-Wire Distances for the 8 TIP Wires

Wire Number	Wire Number	Distance (inch)
1	3	22.00
1	5	33.50
1	7	22.00
3	5	27.75
3	7	32.75
5	7	21.25

Figure 162 shows a diagram of the typical access tube configuration including the CSL tube numbers and the CSL testing combination, temporary casing and drilled shaft diameter and the location of the rebar cage.

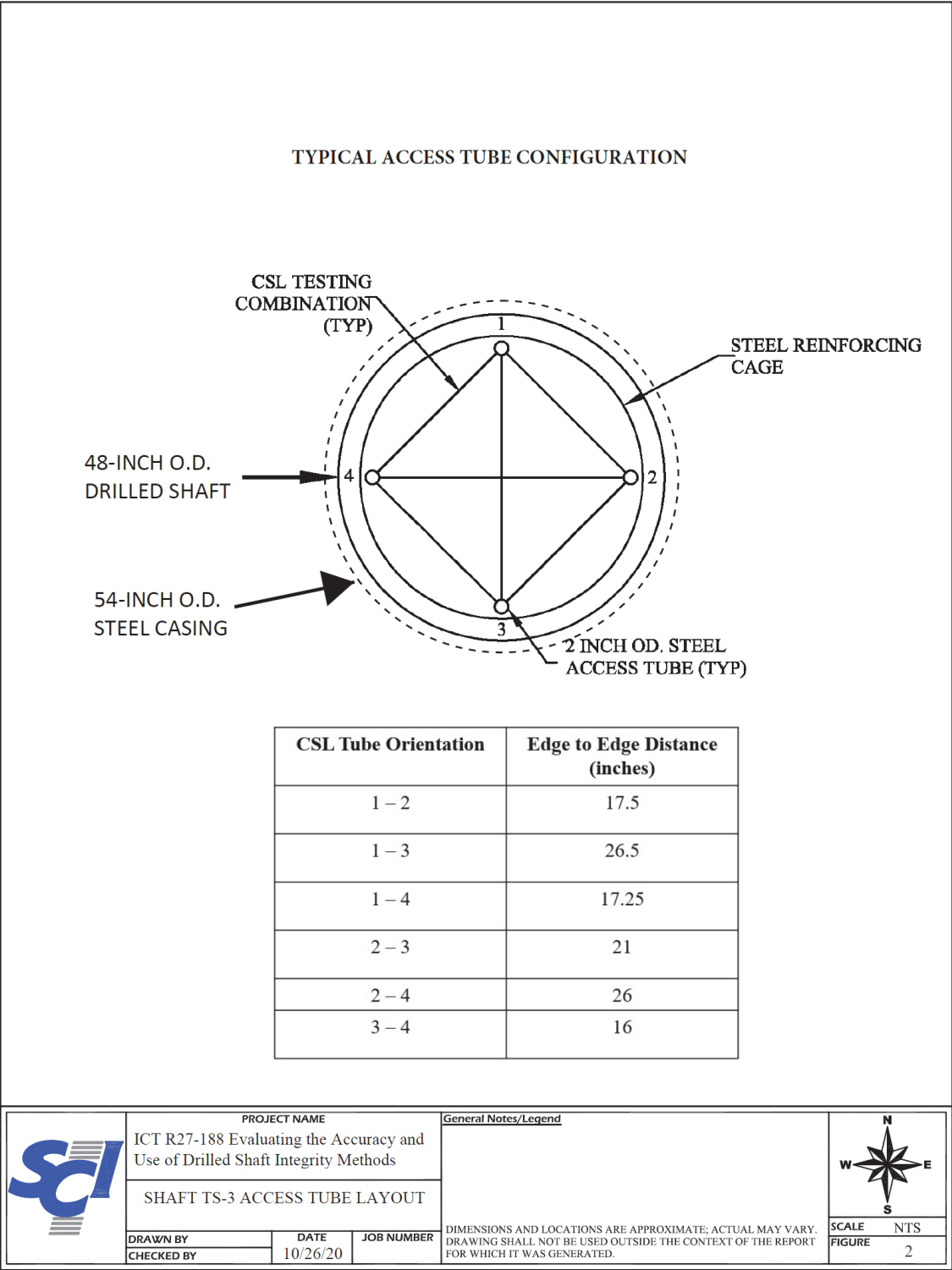


Figure 162. Illustration. CSL access tube configuration log for test drilled shaft #3.

Figure 163 through Figure 165 show the excavation logs for test drilled shaft #3, where the soil encountered is brown silty clay loam to silty loam till up to a depth of approximately 13 ft, medium to hard grey silty fine sand with thick silty layer from approximately 13 ft to 25ft, hard gray silty clay loam to silty loam till from approximately 25 ft to 37 ft at which depth the limestone bedrock was reached. It was reported that the water table was first encountered at depth of approximately 10 ft.

Project Name:	IDOT Test Shaft in Morris, IL	Page	1	of	7
SCI Project No.:	R27-188	R27-188			
Contractor:	Illini Drilled Foundations	Shaft Number:	3		
Inspectors:	T. Stark, J. Lin, A. Idreas and H. Wang- UIUC	Date:	10/26/20		
SCI Reviewer:					

Casing Information					Drilling Information	
ID	OD	TOC Elev.	Length	BOC Elev.		
48	54	572'1"	6	566'1"	Soil Auger Dia. (ft): 4.5/4	
					Rock Core Dia. (ft): 3.5	
					Gnd Surface Elev. (ft): 570	
					Water Table Elev. (ft): 560	
					Reference Elev. (ft): 570	
					Drilling Mud:	
	with casing (shaft)	573'8"	30	543'8"		
48		570"	41'6"	528'6"		

Notes: Casing(C1:4.5') length of 6' (3'11" below ground surface, 2'1" above)

Casing(C2:4') length of 30' (26.33" below ground surface, 3'67" above)

Depth (ft)	Elevation (ft)	Time		Soil Description and Notes
0	570	11:01	In	Approximate 1' of black silty clay loam, then about another 0.7' brown silty clay fill
1.7	568.3	11:09	Out	
1.7	568.3	11:09	In	Brown silty clay loam/ silty loam till /outer casing in after auger
3.93	566.07	11:15	Out	
3.93	566.07	11:20	In	Brown silty clay loam/ silty loam till
6.5	563.5	11:28	Out	
6.5	563.5	11:30	In	Brown silty clay loam/ silty loam till
10	560	11:35	Out	
10	560.5	11:36	In	Collapse sands. Brown coarse sand and some grey silty fine sand at the end of auger
13	557	11:40	Out	
13	557	11:40	In	Grey silty fine sand with thick silty layer
14.5	555.5	11:42	Out	
14.5	555.5	11:43	In	First 2.5' grey fine silty sand then transit to hard grey clay
21	549	11:52	Out	
21	549	11:53	In	hard grey clay, Soil mixture in the boring
25	545	12:25	Out	
25	545	12:26	In	hard grey clay ,Soil mixture in the boring/ after, remove the 4' auger, put the 4' casing in and change the clean bucket to pull out thick mixed clay slurry
26.33	543.67	12:49	Out	
26.33	543.67	1:26	In	Pull out all 9 buckets of slurry, then change to 3.5' rock auger
26.33	543.67	1:46	Out	

Figure 163. Table. Excavation log #1 for test drilled shaft #3.

Project Name:		IDOT Test Shaft in Morris, IL		Page	2	of	7
SCI Project No.:		R27-188		Shaft Group:			
Contractor:		Illini Drilled Foundations		Shaft Number: 3			
Inspectors:		Tim Stark, J. Lin, A. Idreas and H. Wang- UIUC		Date: 10/26/20			
SCI Reviewer:							

Casing Information					Drilling Information	
ID	OD	TOC Elev.	Length	BOC Elev.		
48	54	572'1"	6	566'1"	Soil Auger Dia. (ft):	
		573'8"	30	543'8"	Rock Core Dia. (ft):	
	No casing (shaft)				Gnd Surface Elev. (ft):	
		565'9"	41'6"	528'6"	Water Table Elev. (ft):	
					Reference Elev. (ft):	
					Drilling Mud:	
Notes:						

Depth (ft)	Elevation (ft)	Time		Soil Description and Notes
26.33	543.67	1:51	In	Hard gray silty clay Loam/silty loam till
28	542	1:53	Out	
28	542	1:53	In	
29.5	540.5	1:55	Out	Hard gray silty clay Loam/silty loam till
29.5	540.5	1:56	In	Hard gray silty clay Loam/silty loam till
31	539	1:58	Out	
31	539	1:59	In	
32.5	537.5	2:01	Out	Hard gray silty clay Loam/silty loam till
32.5	537.5	2:01	In	
34	536	2:04	Out	
34	536	2:04	In	Hard gray silty clay Loam/silty loam till
35.5	534.5	2:07	Out	
35.5	534.5	2:09	In	
37	533	2:11	Out	Hard gray silty clay Loam/silty loam till/ reach bedrock
37	533	2:11	In	
38.5	531.5	2:17	Out	Crushed limestone particle mixed with large limestone block
38.5	531.5	2:17	In	
40.5	529.5	2:26	Out	Crushed limestone particle mixed with large limestone block and clean out of bottom
40.5	529.5	2:28	In	
41.5	528.5	2:38	Out	

Figure 164. Table. Excavation log #2 for test drilled shaft #3.

Project Name:	IDOT Test Shaft in Morris, IL	Page	5	of	7
SCI Project No.:	R27-188	Shaft Group:			
Contractor:	Illini Drilled Foundations	Shaft Number:	3		
Inspectors:	Tim Stark, J. Lin, A. Idreas and H. Wang- UIUC	Date:	10/26/20		
SCI Reviewer:	IDOT Test Shaft in Morris, IL				

Type of Drilling Fluid	Reinforcing Cage
Bottom Cleanout Method	Shaft Plumbness Check/4ft
Time/Date Final Cleanout	Proper # Vertical Bars
Top of Rock Elevation (ft)	Proper # Horizontal Bars
Bottom of Rock Elevation (ft)	Side Spacers
Rock Socket Dia, (in)	Bottom Spacers
Shaft Bottom Elev. (ft)	Ties and Connections
Est. Shaft Bottom Dia. (ft)	4

Inspector	Type	Time			
			Start (Prior to Steel Placement)		Test prior to Steel Placement
			Finish (Prior to Steel Placement)		
			Start (Prior to Concrete Placement)		Test prior to Concrete Placement
			Finish (Prior to Concrete Placement)		

Type:

V - Visual

S - Sounding

MS - Mini-SID

N

W

E

NOTES	S	Comments/Recommendations

Results:	Satisfactory	DS Foreman		Date/Time
	Unsatisfactory	SCI Inspector		

Figure 165. Illustration. Excavation log #3 for test drilled shaft #3.

The drilled shaft concrete placement log in Figure 166 shows that there were 3 concrete trucks used with a volume of 9 yd³ for the first two trucks followed by a 5 yd³ truck leading to a total of 23 yd³ of

concrete used for test drilled shaft #3. Figure 167 below shows the summary log for test drilled shaft #3.

DRILLED SHAFT CONCRETE PLACEMENT LOG																																																													
Project Name:		IDOT Test Shaft in Morris, IL		Page		6 of 7																																																							
SCI Project No.:		R27-188		Shaft Group:																																																									
Contractor:		Illini Drilled Foundations		Shaft Number:		3																																																							
Inspectors:		Tim Stark, J. Lin, A. Idreas and H.Wang- UIUC		Date:		10/26/20																																																							
<table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 20%; padding: 2px;">Placement Method</td> <td style="width: 10%; padding: 2px; text-align: center;">X</td> <td style="width: 20%; padding: 2px;">Tremie</td> <td style="width: 20%; padding: 2px;">Volume in Pump Truck</td> <td style="width: 5%; padding: 2px; text-align: center;">#</td> <td style="width: 10%; padding: 2px;">ID</td> <td style="width: 10%; padding: 2px;">Length</td> <td style="width: 15%; padding: 2px;">Vol.</td> </tr> <tr> <td></td> <td></td> <td style="padding: 2px;">Pumped</td> <td style="padding: 2px;">Pump Truck Lines</td> <td></td> <td></td> <td></td> <td style="padding: 2px;">yd³</td> </tr> <tr> <td></td> <td></td> <td></td> <td style="padding: 2px;">Pump Truck Hopper</td> <td></td> <td></td> <td></td> <td style="padding: 2px;">yd³</td> </tr> </table>								Placement Method	X	Tremie	Volume in Pump Truck	#	ID	Length	Vol.			Pumped	Pump Truck Lines				yd ³				Pump Truck Hopper				yd ³																														
Placement Method	X	Tremie	Volume in Pump Truck	#	ID	Length	Vol.																																																						
		Pumped	Pump Truck Lines				yd ³																																																						
			Pump Truck Hopper				yd ³																																																						
Ref. Elev.		570'																																																											
		C1:572'1"																																																											
TOC Elev.		C2:573.67'																																																											
TOS Elev.		570'		Total Volume in Lines + Pump Truck		Σ = 9 yd ³																																																							
TOR Elev.		533'																																																											
		C1:566.08'																																																											
BOC Elev.		C2:543.67'		Time First Truck Batched:		4:15 pm																																																							
BOR Elev.		533'		Depth of Water per Hour Inside Shaft (Dry Hole Check):																																																									
BOS Elev.		543.67'		Rebar Cage Top Elev (Start):		(Finish):																																																							
<table border="1" style="width: 100%; border-collapse: collapse; text-align: center;"> <thead> <tr> <th>Truck No.</th> <th>Concrete volume (cy)</th> <th>Arrival time</th> <th>Round</th> <th>Start time</th> <th>Finish time</th> <th>Tremie depth at beginning (ft) (From ground surface)</th> <th>Depth to concrete at beginning (ft) (From ground surface)</th> <th>Depth to concrete at end (ft) (From ground surface)</th> </tr> </thead> <tbody> <tr> <td rowspan="2">1</td> <td rowspan="2">9</td> <td rowspan="2">4:15</td> <td>1</td> <td>4:28</td> <td>4:34</td> <td>40</td> <td>40 (no concrete)</td> <td>30</td> </tr> <tr> <td>2</td> <td>4:34</td> <td>4:38</td> <td>26</td> <td>30</td> <td>23</td> </tr> <tr> <td rowspan="3">2</td> <td rowspan="3">9</td> <td rowspan="3">4:42</td> <td>1</td> <td>4:50</td> <td>4:57</td> <td>26</td> <td>23</td> <td>12</td> </tr> <tr> <td>2</td> <td>4:57</td> <td>5:07</td> <td>10</td> <td>12</td> <td>5.5</td> </tr> <tr> <td>3</td> <td>5:12</td> <td>5:14</td> <td>8</td> <td>5.5</td> <td>5</td> </tr> <tr> <td>3</td> <td>5</td> <td>5:32</td> <td>1</td> <td>5:40</td> <td>5:48</td> <td>8</td> <td>5</td> <td>0.5</td> </tr> </tbody> </table>								Truck No.	Concrete volume (cy)	Arrival time	Round	Start time	Finish time	Tremie depth at beginning (ft) (From ground surface)	Depth to concrete at beginning (ft) (From ground surface)	Depth to concrete at end (ft) (From ground surface)	1	9	4:15	1	4:28	4:34	40	40 (no concrete)	30	2	4:34	4:38	26	30	23	2	9	4:42	1	4:50	4:57	26	23	12	2	4:57	5:07	10	12	5.5	3	5:12	5:14	8	5.5	5	3	5	5:32	1	5:40	5:48	8	5	0.5
Truck No.	Concrete volume (cy)	Arrival time	Round	Start time	Finish time	Tremie depth at beginning (ft) (From ground surface)	Depth to concrete at beginning (ft) (From ground surface)	Depth to concrete at end (ft) (From ground surface)																																																					
1	9	4:15	1	4:28	4:34	40	40 (no concrete)	30																																																					
			2	4:34	4:38	26	30	23																																																					
2	9	4:42	1	4:50	4:57	26	23	12																																																					
			2	4:57	5:07	10	12	5.5																																																					
			3	5:12	5:14	8	5.5	5																																																					
3	5	5:32	1	5:40	5:48	8	5	0.5																																																					
<table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 20%; padding: 2px;"></td> <td style="width: 10%; padding: 2px;">OD</td> <td style="width: 10%; padding: 2px;">Top Elev.</td> <td style="width: 10%; padding: 2px;">Bot. Elev.</td> <td style="width: 10%; padding: 2px;">Start</td> <td style="width: 10%; padding: 2px;">Finish</td> <td style="width: 10%; padding: 2px;"></td> <td style="width: 10%; padding: 2px;">Rebar Cage</td> </tr> <tr> <td style="padding: 2px;">Temp Casing Removal</td> <td colspan="5" style="padding: 2px;"></td> <td style="padding: 2px;">Centered:</td> <td style="padding: 2px;"></td> </tr> <tr> <td style="padding: 2px;"></td> <td colspan="5" style="padding: 2px;"></td> <td style="padding: 2px;">Re-Centered:</td> <td style="padding: 2px;"></td> </tr> </table>									OD	Top Elev.	Bot. Elev.	Start	Finish		Rebar Cage	Temp Casing Removal						Centered:								Re-Centered:																															
	OD	Top Elev.	Bot. Elev.	Start	Finish		Rebar Cage																																																						
Temp Casing Removal						Centered:																																																							
						Re-Centered:																																																							
Notes: _____																																																													

Figure 166. Table. Concrete placement log for test drilled shaft #3.

Drilled Shaft Summary Log

Project Name:	IDOT Test Shaft in Morris, IL	Page	7	of	7
SCI Project No.:	R27-188	Shaft Group:			
Contractor:	Illini Drilled Foundations	Shaft Number:	3		
Inspectors:	Tim Stark, J. Lin, A. Idreas and H.Wang- UIUC	Date:	10/26/2020		

Date Cased	10/26/2020	
Date Opened	10/26/2020	Casing Type
Date Concrete Placed	10/26/2020	Casing Outside Diameter (OD) (ft)
		Bot. Of Casing (BOC) Elev. (ft)
		Top Of Casing (TOC) Elev. (ft)
		Dia. of Rock Socket (ft)
		Shaft Diameter (ft)

Const.	Temp.
	X
	48
	573.67
	543.67
	3.5
	4

Ground Surface Elevation (ft)	570
Wet & Dry Shaft Length (ft)	10
Rock Socket Length (ft)	4.5
Top Of Shaft (TOS) Elevation (ft)	570
Bot. Of Shaft (BOS) Elevation (ft)	528.5
Constructed Shaft Length (ft)	41.5
Reinforcing Steel Cage Placed	yes

Volume of Concrete			
Design Mix			
Theoretical (VTh)	18.5 yd ³	Actual (VP)	23 yd ³
OP (VP-VTh)		UP (VTh - VP)	
Duration (min)			

Legend:

TOC	Top Of Casing
TOG	Top Of Ground
TOS	Top Of Shaft
TOR	Top Of Rock
BOC	Bottom Of Casing
BOS	Bottom Of Shaft
BOR	Bottom Of Rock

Contractor: Illini Drilled Foundations

Notes:

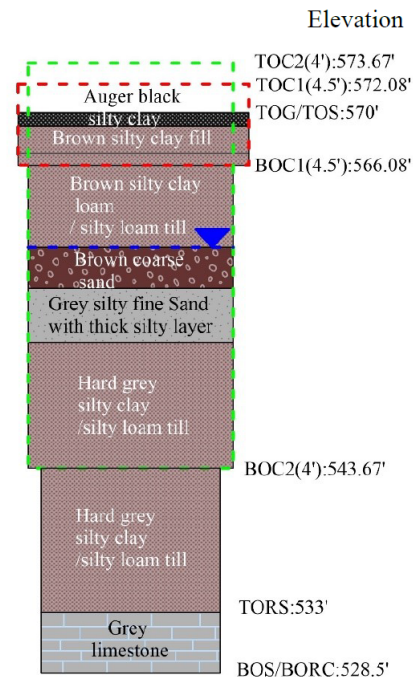


Figure 167. Illustration. Drilled shaft summary log for test drilled shaft #3.

APPENDIX F: RECOMMENDED SPECIFICATION FOR THERMAL INTEGRITY PROFILE TESTING OF DRILLED SHAFTS

Description. This work shall consist of furnishing and installing materials and equipment necessary to perform Thermal Integrity Profile (TIP) testing of drilled shafts according to Illinois Modified ASTM D7949. Data collection using embedded thermal sensors shall be performed on all drilled shafts identified on the plans. Analysis and reports shall be performed only on selected drilled shafts where specified and as directed by the Engineer. This work includes collection, analysis, and storage of the TIP data, preparation of reports summarizing the TIP data, and investigating anomalies identified in the TIP data.

Qualifications. A consulting firm experienced in TIP testing shall direct this work. The TIP consulting firm shall be a company independent from the Contractor with a minimum of 3 years of experience performing TIP testing of drilled shafts. The individual evaluating the TIP data and preparing the report shall be an Illinois Licensed Professional Engineer and have experience on a minimum of 5 TIP testing projects.

The name, contact information, and qualifications of the TIP consulting firm, including the names and experience of the individual employees performing and analyzing the test results and preparing the report, shall be submitted to the Engineer at least 30 days prior to drilled shaft construction.

Training. The TIP Consultant shall provide on-site instruction to the Contractor on the installation of the embedded thermal sensors and data recording devices, use of the data recording apparatus, use of the processing and display apparatus, and methods of transferring data to the TIP Consultant.

Construction. Embedded thermal sensors shall be installed on all drilled shafts identified on the plans according to the Illinois Modified ASTM D7949. Embedded thermal sensors shall be checked for functionality after the reinforcing cage has been placed in the shaft excavation. Any embedded thermal sensors that are not functioning correctly shall be removed and replaced.

In wet installations, embedded thermal sensors shall have enough lead in wire to allow for connection of the recording apparatus above the water.

The TIP data shall be recorded and stored for each shaft where embedded thermal sensors are installed. Analysis and reports shall be performed only on selected drilled shafts where specified and as directed by the Engineer. The Engineer may direct additional analysis and reports, if necessary, due to problems encountered or observed during drilled shaft construction. The Engineer will determine which shaft(s) shall have an analysis and report prepared. All drilled shafts that do not require an analysis and report shall have the raw data submitted according to Illinois Modified ASTM D7949.

Superimposed loads, either dead or live, shall not be applied to a drilled shaft until TIP testing is completed, TIP reports have been submitted, any necessary testing and repairs have been completed, and permission has been granted by the Engineer.

Reports. Reports shall be according to Illinois Modified ASTM D7949. Reports shall identify, label, and discuss anomalies, potential flaws, or defects. If none are identified, that shall be stated in the report. Reports shall discuss recommendations for additional investigation or testing of anomalies, flaws, or defects identified. Reports shall give an overall assessment of the constructed shaft quality based on the data and information analyzed. Reports shall be submitted to the Bureau of Bridges and Structures, or local agency owner, for review and acceptance.

Anomalies. If anomalies are identified, they shall be investigated by coring or other methods approved by the Engineer. If coring is to be performed, the Engineer will determine the location of the core(s).

Remediation of Drilled Shaft Defects. When the Engineer determines that a defect is present, the Engineer will direct the Contractor to repair the defect. The Contractor shall submit a plan to repair the defect to the Engineer for approval. No compensation will be made for remedial work, or losses, or damage, due to remedial work of drilled shafts found defective or not in accordance with the drilled shaft specifications or plans. Modifications to the structure shall be designed, detailed, and sealed by an Illinois Licensed Structural Engineer.

Method of Measurement. TIP testing materials, equipment, and data collection will be measured for payment by the linear foot of drilled shafts instrumented. Each individual embedded thermal sensor wire will not be measured for payment.

TIP test analysis and reporting will be measured for payment for each drilled shaft where analysis and reporting is specified or directed by the Engineer.

Investigation of anomalies will not be measured for payment.

Basis of Payment. TIP materials, equipment, and data collection will be paid for at the contract unit price per lineal foot for THERMAL INTEGRITY PROFILE DATA COLLECTION. TIP test analysis and reporting will be paid for at the contract unit price per each for THERMAL INTEGRITY PROFILE TESTING.

ILLINOIS MODIFIED ASTM D7949, Method B

Standard Test Method for
Thermal Integrity Profiling of Concrete Deep Foundations, Method B
Reference ASTM D7949-14

The testing shall be per ASTM D7949-14, Method B, except as modified herein. All references to the Method A procedure shall be disregarded.

ASTM SECTION	Illinois Modification														
1.6	Revise this section as follows: Units—The values stated in either English units or SI units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in nonconformance with the standard. Reporting of test results in units other than English units shall not be regarded as nonconformance with this standard.														
3.2	Add the following to this section: 3.2.12 anomaly, n - irregularity or series of irregularities observed in a thermal profile indicating a possible flaw.														
6.1, 6.2, 6.2.1, 6.3.1, 6.3.2, 6.3.3, & 6.3.4	Delete these sections.														
6.4.1	Revise the first sentence of this section as follows: The recording apparatus shall record depth and temperature data from each group of embedded thermal sensors at a depth interval of no greater than 300 mm.														
7.1	Revise this section as follows: The embedded thermal sensors shall be installed during construction of the foundation element. The location plan shall provide access locations for embedded thermal sensors according to the following table. <table border="1"> <thead> <tr> <th>Reinforcing Cage Diameter (feet)</th><th>Number of access locations for embedded thermal sensors</th></tr> </thead> <tbody> <tr> <td>≤ 5.0</td><td>4</td></tr> <tr> <td>5.1 to 7.0</td><td>6</td></tr> <tr> <td>7.1 to 9.0</td><td>8</td></tr> <tr> <td>9.1 to 11.0</td><td>10</td></tr> <tr> <td>11.1 to 13.0</td><td>12</td></tr> <tr> <td>> 13.0</td><td>14</td></tr> </tbody> </table> Access locations for embedded thermal sensors shall be spread equally around the perimeter and spaced at an equal distance from the axis, and the sensor levels shall be the same for all of the access locations with a maximum depth interval between levels of 300 mm. Fig 3 illustrates several plan layout configurations for the access locations.	Reinforcing Cage Diameter (feet)	Number of access locations for embedded thermal sensors	≤ 5.0	4	5.1 to 7.0	6	7.1 to 9.0	8	9.1 to 11.0	10	11.1 to 13.0	12	> 13.0	14
Reinforcing Cage Diameter (feet)	Number of access locations for embedded thermal sensors														
≤ 5.0	4														
5.1 to 7.0	6														
7.1 to 9.0	8														
9.1 to 11.0	10														
11.1 to 13.0	12														
> 13.0	14														

ILLINOIS MODIFIED ASTM D7949, Method B
Standard Test Method for
Thermal Integrity Profiling of Concrete Deep Foundations, Method B
Reference ASTM D7949-14

ASTM SECTION	Illinois Modification
7.1.2	Revise this section as follows: Temperature measurements shall be performed starting at the beginning of concrete placement in the element and terminating a minimum of 12 hours after the peak temperature of the concrete has been reached. The tests should be performed, analyzed, and reported on the selected shaft(s) at the time of ½ peak temperature, and at the time of peak temperature of the concrete.
7.2, 7.2.1, 7.2.2, 7.2.3, & 7.2.4	Delete these sections.
7.3.1	Revise the third sentence of this section as follows: Embedded thermal sensors shall extend to the bottom of the foundation element.
7.4, 7.4.1, 7.4.2, 7.4.3, 7.4.4, 7.4.5, 7.4.6, 7.4.7, 7.4.8, & 7.4.9	Delete these sections.
7.5.3	Revise this section as follows: Connect each embedded thermal sensor to the Recording Apparatus. Start recording temperature data to the nearest 0.1°C prior to concrete placement. Record temperatures periodically at intervals not to exceed 15 minutes. Testing shall be terminated only after a minimum of 12 hours has elapsed after the peak temperature of the concrete has been reached.
7.6.1	Delete this section.
8.1.1 (New Section)	Add as follows: Test data and results shall be reported in US Customary units.
8.5 (New Section)	<i>Raw Data Submittal</i> – The raw temperature data for the peak temperature time and ½ the peak temperature time shall be provided to the Engineer for each drilled shaft where data was collected. The data shall be clearly labeled and organized in a standard computer spreadsheet format. The data shall be provided in a table and in a graph.

APPENDIX G: RECOMMENDED SPECIFICATION FOR CROSSHOLE SONIC LOGGING TESTING OF DRILLED SHAFTS

Description. This work shall consist of furnishing and installing materials and equipment necessary to install access ducts in all drilled shafts of structures identified on the plans, and to perform Crosshole Sonic Logging (CSL) testing, analysis, and reports only on selected drilled shafts where specified and as directed by the Engineer. This work shall be according to Illinois Modified ASTM D6760. This work includes investigating anomalies identified in the CSL data and grouting of all access ducts after testing and analysis.

Materials. Materials shall be according to the following.

- (a) Nonshrink Grout (Note 1).....1024.02
Note 1. Grout shall attain a minimum strength equal to the required strength of the drilled shaft concrete at 14 days.

Qualifications. A consulting firm experienced in CSL testing shall conduct this work. The CSL consulting firm shall be a company independent from the Contractor with a minimum of 3 years of experience in performing CSL testing of drilled shafts. The individual evaluating the CSL data and preparing the report shall be an Illinois Licensed Professional Engineer and have experience on a minimum of 5 CSL testing projects.

The name, contact information, and qualifications of the CSL consulting firm, including the names and experience of the individual employees performing and analyzing the test results and preparing the report, shall be submitted to the Engineer at least 30 days prior to drilled shaft construction.

Construction. Access ducts shall be placed in all drilled shafts identified on the plans according to Illinois Modified ASTM D6760. The completed rebar cage with the required access ducts shall be lifted to prevent cage bending and damage to the access ducts and/or joints. Joints of the access ducts shall be watertight.

The Engineer will determine which drilled shafts shall have CSL testing performed after the concrete has been placed, and may direct additional tests, if necessary, due to problems encountered or observed during drilled shaft construction.

After permission is given by the Engineer, the access ducts shall be grouted. The grout shall be placed with a pump, starting at the bottom of each access duct.

Superimposed loads, either dead or live, shall not be applied to a drilled shaft until CSL testing is completed, CSL reports have been submitted, any necessary testing and repairs have been completed, access ducts have been grouted, and permission has been granted by the Engineer.

Reports. Reports shall be according to Illinois Modified ASTM D6760. Reports shall identify, label, and discuss anomalies, potential flaws, or defects. If none are identified, that shall be stated in the report. An anomalous zone shall be defined as an area where the First Arrival Time (FAT) increase exceeds 20 percent of the local average FAT value of the shaft concrete at the time of testing. Reports shall discuss recommendations for additional investigation or testing of anomalous zones identified. Reports shall give an overall assessment of the constructed shaft quality based on the data and information analyzed. Reports shall be submitted to the Bureau of Bridges and Structures, or the local agency owner, for review and acceptance.

Anomalies. If anomalies are identified, they shall be investigated by coring or other methods approved by the Engineer. If coring is to be performed, the Engineer will determine the location of the core(s).

Remediation of Drilled Shaft Defects. When the Engineer determines a defect is present, the Engineer will direct the Contractor to repair the defect. The Contractor shall submit a plan to repair the defect to the Engineer for approval. No compensation will be made for remedial work, or losses, or damage, due to remedial work of drilled shafts found defective or not in accordance with the drilled shaft specifications or plans. Modifications to the structure shall be designed, detailed, and sealed by an Illinois Licensed Structural Engineer.

Method of Measurement. Installation and grouting of access ducts will be measured for payment by the linear foot of drilled shafts with access ducts. Each individual access duct will not be measured for payment.

CSL testing, analysis, and reporting will be measured for payment by each drilled shaft foundation tested.

Investigation of anomalies will not be measured for payment.

Basis of Payment. Installation and grouting of access ducts will be paid for at the contract unit price per lineal foot for CROSSHOLE SONIC LOGGING ACCESS DUCTS. CSL testing, analysis, and reporting will be paid for at the contract unit price per each for CROSSHOLE SONIC LOGGING TESTING.

ILLINOIS MODIFIED ASTM D6760

Standard Test Method for

Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing

Reference ASTM D6760-16

ASTM SECTION	Illinois Modification								
1.7	Revise this section as follows: Units—The values stated in either English units or SI units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in nonconformance with the standard. Reporting of test results in units other than English shall not be regarded as nonconformance with this standard.								
3.1.1	Revise this section as follows: <i>access ducts, n</i> – preformed steel tubes or drilled boreholes, placed in the concrete to allow probe entry in pairs to measure pulse transmission in the concrete between the probes.								
5.2.1	Revise the first sentence of this section as follows: For crosshole tests, the access ducts shall be made of steel to prevent debonding of the access duct from the concrete resulting in an anomaly.								
5.2.2	Delete this section.								
6.1	Revise the second sentence of this section as follows: The access ducts shall be mild steel with internal diameter of 38 mm (1.5 in.). Delete the third, fourth, and fifth sentences of this section.								
7.1.1	Revise this section as follows: The access ducts shall be installed during construction of the drilled shaft. For drilled shafts foundations, access ducts shall be provided according to the following table. <table border="1"> <thead> <tr> <th>Reinforcing Cage Diameter (feet)</th><th>Number of Access Ducts</th></tr> </thead> <tbody> <tr> <td>≤ 5.0</td><td>4</td></tr> <tr> <td>5.1 to 7.0</td><td>6</td></tr> <tr> <td>> 7.0</td><td>8</td></tr> </tbody> </table> Access ducts shall be spread equally around the perimeter and spaced at an equal distance from the axis. Delete Fig. 4 in Section 7.1.1.	Reinforcing Cage Diameter (feet)	Number of Access Ducts	≤ 5.0	4	5.1 to 7.0	6	> 7.0	8
Reinforcing Cage Diameter (feet)	Number of Access Ducts								
≤ 5.0	4								
5.1 to 7.0	6								
> 7.0	8								

ILLINOIS MODIFIED ASTM D6760
Standard Test Method for
Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing

Reference ASTM D6760-16

7.1.2	Revise the second sentence of this section as follows: The exterior duct surface shall be free from contamination (for example, oil, dirt, loose rust, mill scale, etc.) to ensure a good bond between the duct surface and the surrounding concrete.
7.1.3	Delete the third sentence of this section.
7.2	Revise the first sentence of this section as follows: The access ducts shall be installed such that the bottom of the access ducts are at the bottom of the concrete deep foundation element so that the bottom of the drilled shaft can be tested. Revise the sixth sentence of this section as follows: Access ducts shall be filled with water prior to concrete placement to assure good bonding of the concrete to the duct after the concrete cools. The access ducts shall be kept full of water until the ducts are grouted.
7.3	Revise the first sentence of this section as follows: In cases where drilled shafts to be tested have access ducts that do not permit passage of the probes, do not retain water, are not plumb, are debonded from the concrete, or cannot be used for testing for other reasons, drilled boreholes shall be used to provide probe access.
7.4.2	Revise the second sentence of this section as follows: The tests shall be performed no later than 21 days after concrete casting.
7.6	Delete this section.
7.8.1	Revise the first sentence of this section as follows: If the ultrasonic profile indicates an anomaly, then the suspect anomaly zone shall be further investigated by special test procedures such as fan shaped tests, tests with the probes raised at a fixed offset distance, or other tomographical techniques.
7.8.2	Delete Note 4 of this section.
8.1.1 (New Section)	Add as follows: Test data and results shall be reported in US Customary units.

APPENDIX H: CONSTRUCTION INSPECTOR'S CHECKLIST FOR DRILLED SHAFTS

State of Illinois
Department of Transportation

While its use is not required, this checklist has been prepared to provide the field inspector a summary of easy-to-read step-by-step requirements relative to the proper construction of Drilled Shafts (Section 516 of the Standard Specifications). The following questions are based on information found in the Standard Specifications, Guide Bridge Special Provision No. 86 "Drilled Shafts", Guide Bridge Special Provision No. 91 "Crosshole Sonic Logging Testing of Drilled Shafts", Guide Bridge Special Provision No. 92 "Thermal Integrity Profile Testing of Drilled Shafts", Project Procedures Guide, Construction Manual, and Drilled Shaft Foundation Construction Inspection Class Reference Guide.

1) Prior to Construction

- a) Have you checked the Special Provisions, Supplemental Specifications and plans to see if any modifications have been made to the requirements listed herein? _____
- b) When specified for the construction item, has the Contractor submitted a Drilled Shaft Qualifications and Installation Plan (Form BBS 133)? _____
- c) Has the Drilled Shaft Qualifications and Installation Plan been approved by the Bureau of Bridges and Structures (BB&S)? _____
- d) If Drilled Shaft Integrity Testing (CSL or TIP) is specified as a construction item, has the Contractor submitted their Integrity Testing Consultant's Qualifications submittal? _____
- e) Has a Drilled Shaft Construction Pre-Drill Meeting been scheduled, and has an agenda been prepared? _____
- f) Does the Contractor have an approved concrete mix design? _____
- g) Is the concrete mix design nominal maximum aggregate size appropriate for the rebar spacing, and for the clear distance between the rebar and permanent casing or shaft wall? _____
- h) Has a trial batch to determine slump retention been scheduled if temporary casing or the Slurry Method of construction will be used? _____
- i) Will the rate of concrete placement be adequate for the slump retention time period? _____

2) Equipment and Casing

- a) Does the Contractor have the proper equipment for inspection of the shafts such as lighting? _____

- b) Has the Contractor provided access for the inspector at the top of the drilled shafts with the appropriate railings and other safety equipment? _____
- c) Do you have a weighted tape measure to measure the length of the drilled shafts and to inspect the shaft bottom for cleanliness? _____
- d) Does the Contractor have all the equipment/tools listed in the Drilled Shaft Installation plan for excavation and cleaning of the shaft? _____
- e) If the Contractor will construct the shaft using a slurry, is the proper equipment for testing density, viscosity, pH, and sand content on site? _____
- f) Does the Contractor have the proper slurry mixing equipment to construct the shaft? _____
- g) Is a desander required, and does the Contractor have it on site and operational? _____
- h) Is the tremie or pump pipe steel, clean, smooth, and are the connections watertight? _____
- i) Is the tremie pipe a minimum diameter of 10 inches? _____
- j) Is the pump pipe a minimum diameter of 4 inches? _____
- k) If a drop chute will be used, will the free fall of concrete be no more than 60 feet for conventional concrete and 30 feet for self-consolidating concrete? _____
- l) Is the permanent casing the correct diameter, thickness, and length per Article 1006.05(d) and the plans? _____
- m) Is the temporary casing interior free from concrete? _____
- n) If the Contractor proposed to use a permanent casing at locations where not called for on the plans, has the Bureau of Bridges and Structures given approval? _____
- o) If TIP testing drilled shafts is specified by the contract, has the TIP Consultant provided on-site instruction on the data collection equipment to the Contractor and Engineer in accordance with the special provision? _____

3) Shaft Excavation & Cleaning

- a) Are you completing the Drilled Shaft Excavation and Inspection Record (Form BBS 134)? _____
- b) Have procedures been discussed with the Contractor in the event obstructions or differing site conditions are encountered? _____
- c) Are there survey markings to properly establish the location of the drilled shaft? _____
- d) Is the shaft being constructed within 3 in. of the plan station and offset at the top of the shaft? _____
- e) Is there a benchmark to locate shaft elevations? _____

- f) Is the top of shaft elevation no more than 1 in. above and no more than 3 in. below the plan elevation? _____
- g) Is the shaft diameter correct? _____
- h) Is the slurry level being maintained a minimum of 5 feet above the height required to prevent caving of the shaft? _____
- i) Is slurry testing being performed during excavation, and the sample obtained within 2 feet of the bottom and at mid-height of the shaft excavation? _____
- j) If bellling is required, does the bell size and geometry match the plans? _____
- k) Is the shaft plumb and does not exceed 1.5% for out of vertical plumbness? _____
- l) Is the shaft of proper plan depth when in soil? _____
- m) Is the shaft of proper depth below top of rock encounter? _____
- n) If the top of rock elevation differs from that shown on the plans by more than 10% of the length of the drilled shaft above the rock, has BB&S or the design engineer been notified? _____
- o) If terminated in soil, does the shaft bottom have a maximum of 1 ½ inches of sediment or debris? _____
- p) If terminated in rock, does the shaft bottom have a maximum ½ inch of sediment or debris? _____
- q) If bellling is required, are the remaining spoils being back-bladed to the bell periphery with a 1 foot over-sized bucket? _____
- r) Is the Contractor reaming the sides of the shaft because they have been slickened by auger trimmings? _____
- s) Is the Contractor reaming the sides of the shaft because the sidewall has softened, swelled, or has a buildup of slurry cake? _____

4) Reinforcing Cage

- a) Does the grade of steel shown on the plans match the mill certificate? _____
- b) Does the rebar number, sizes, spacing, lengths, and clearances match the plans? _____
- c) Is the rebar tied at the intersection frequency specified in Section 508? _____
- d) Was the rebar lapped or mechanically spliced in accordance with contract documents? _____
- e) If applicable, is cross bracing being installed to prevent rebar cage deformation during lifting? _____
- f) Is the cross bracing installed so that a clear path is available for the pump pipe or tremie to reach the bottom of the drilled shaft during concrete placement? _____
- g) Does the rebar cage diameter match the plans and the rebar cage length meet field drilled conditions? _____

- h) When specified, are plastic chairs or clearance boots being used to provide concrete cover between the base of the drilled shaft and the rebar cage? _____
- i) Is the Contractor using non-corrosive rolling spacers for the rebar cage? _____
- j) Are the rolling spacers no greater than 10 feet apart along the length of the rebar cage, and within 2 feet of both the top and bottom of the shaft? _____
- k) Is there one rolling spacer for each 1.0 foot of shaft diameter present around the perimeter of the rebar cage, with a minimum of 4 spacers at each level? _____
- l) Is the center of the rebar cage within 1.5 inch of plan station and offset at the top of the shaft? _____
- m) Is the rebar cage plumb and does not exceed 0.83% (or 0.1 inch per foot of depth) for out of vertical plumbness? _____
- n) Is the top of the rebar cage no more than 1 inch above and no more than 3 inches below the plan elevation? _____
- o) Is the rebar cage free from mud and debris when placed in the hole? _____
- p) Is the rebar cage free from deformation after placement in the hole? _____
- q) When Cross-hole Sonic Logging (CSL) testing has been specified, have the steel access ducts for testing been installed in all shafts at the proper spacing, adequately secured, and maintained in straight alignment for the full length of the shaft? _____
- r) Are the CSL access ducts of the size and number as specified? _____
- s) Are access ducts assembled with joints and caps that prevent leaking? _____
- t) Do access ducts extend to the bottom of the shaft? _____
- u) Have the access ducts for CSL testing been filled with water, watertight, and maintained full of water prior to concrete placement to prevent debonding during concrete curing because of heat of hydration? _____
- v) Is the completed rebar cage with the required access ducts lifted to prevent cage bending and damage to the access ducts and/or joints? If not, have any of the joints of the access ducts been damaged? If damage occurred, has the damage been repaired? Note that the joints in the access ducts are not to be covered with duct tape or other similar products. _____
- w) When Thermal Integrity Profile (TIP) testing has been specified, have the embedded thermal sensor wires been installed in all shafts and adequately secured? _____
- x) Are the required number of embedded thermal sensor wires for TIP testing provided? _____
- y) Are the embedded thermal sensor wires evenly spaced around the perimeter of the reinforcing cage? _____

- z) Do the embedded thermal sensor wires extend to the bottom of the cage for all shafts? _____
- aa) Have the embedded thermal sensors for TIP testing been checked for functionality before and after the reinforcing cage has been placed in the shaft excavation and prior to concrete placement? _____
- bb) Has the TIP data transfer equipment been set-up, tested, and functioning prior to concrete placement? _____
- cc) In wet installation, do the embedded thermal sensors for TIP testing have enough lead in wire to allow for connection of the recording apparatus above the water? _____
- dd) If conditions differ such that the length of shaft is increased, does the Contractor have additional reinforcement bars, splicers, CSL access ducts or TIP sensor wires (if applicable), readily available to extend the cage to bottom of excavation as required? _____
- ee) Is the rebar cage checked for settling and floating during concrete placement? _____

5) Concreting Operations

- a) Are you completing the Drilled Shaft Concrete Placement Log (Form BBS 135)? _____
- b) Did you use weighted tape to measure depth to bottom of shaft in several locations for comparison with design and verify clean-out? _____
- c) If TIP testing is required, has the Contractor started recording data from thermal sensors for TIP testing at the beginning of concrete placement? _____
- d) Is concrete placement beginning within 1 hour of shaft cleaning and inspection? _____
- e) Prior to concrete placement, has the slurry been tested 1 hour before concrete placement and the sample obtained within 2 feet of the base excavation? _____
- f) At the time the temporary casing is being broken loose, is the head pressure inside the casing a minimum of 1.25 times the head pressure outside the casing (but in no case shall the top of concrete be less than 5 feet above the bottom of the casing)? _____
- g) At the time of temporary casing removal, is the concrete slump a minimum of 6 inches? _____
- h) Is the minimum tremie or pump discharge end embedment in concrete being maintained as the temporary casing is pulled? _____
- i) For tremie or concrete pump placement, is the discharge end being embedded in the concrete a minimum of 10 feet throughout concrete placement when displacing water or slurry? _____
- j) Is tremie or pumped concrete placement occurring without interruption? If not, document the time of interruption. _____
- k) For Free Fall Placement, is the rate of water infiltration into the shaft excavation less than 12 in. per hour, and is there less than 3 inches of standing water in the base of the shaft at the time of _____

concrete placement?

- l) For Free Fall Placement, is the flow of concrete directed down the center of the shaft to avoid rebar? _____
- m) For Free Fall Placement, is the top 10 feet of concrete in the shaft being vibrated? _____
- n) For Free Fall Placement, is the fall distance of the concrete less than 60 feet for conventional concrete or less than 30 feet for self-consolidating concrete? _____
- o) For the Slurry Method of construction, is the slump a minimum of 6 inches for all concrete placed at the end of the pour? _____
- p) Is the Contractor over pouring the shaft until 18 inches of good quality, uncontaminated concrete is expelled at the top? _____
- q) Are temperature, slump, air content, and strength tests being performed as required? _____
- r) Recommended Only: Is slump retention being monitored during the pour, and is a strength test being performed on the shaft concrete after all contaminated concrete is expelled? _____

6) Post Installation

- a) Is the concrete being cured and protected according to Article 1020.13? _____
- b) If applicable, have access ducts for CSL testing been checked for water level no more than one hour after completion of concrete placement? Note any significant drop in water levels, top off, and re-check later. _____
- c) If removable forms are used has the concrete reached a minimum compressive strength of 2,500 psi, and cured for a minimum of 72 hours before the forms are removed? _____
- d) Is all casing removed to the proper elevation? _____
- e) Have all gaps or voids between the shaft excavation and the permanent casing been grouted? _____
- f) Have you documented the pay items? _____
- g) Has the Contractor performed any required non-destructive testing and is it being performed within the specified time frame? _____
- h) Has the Engineer selected the drilled shaft(s) for CSL or TIP analysis and report preparation by the Contractor's testing Consultant? The Engineer is advised to provide the BBS 134 and BBS 135 forms to the Consultant. _____
- i) Has the Contractor's testing Consultant submitted the required CSL or TIP analysis reports for the selected shafts? _____
- j) Has the CSL or TIP testing report(s) been submitted to the Bureau of Bridges and Structures, or local agency owner, for review? _____

- k) Has the CSL or TIP testing report(s) been approved? Are any remediation measures required? —
- l) Has the Engineer received the raw data submittal for drilled shafts where TIP data was collected, but an analysis and report were not required? —
- m) Have all field inspections, material verifications, on-site observations, as-built conditions, and testing reports been documented? —
- n) Based on thorough inspections, observations, and testing, is the shaft acceptable and approved by the Engineer? —
- o) After all shafts in a substructure location or grouping have been accepted, have the CSL access ducts been properly grouted prior to construction on the drilled shaft(s)? —



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