ESTIMATING THE AS-PLACED GROUT VOLUME OF AUGER CAST PILES – PART 1

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Final Report

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Disclaimer

Approximate Conversions to SI Units

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fL	foot-Lamberts	3.426	candela/m^2	cd/m^2
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
kip	kilopound	4.45	kilonewtons	kN

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T

SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2
kN	kilonewtons	0.225	kilopound	kip

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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Auger cast piles have historically been used for private industry applications but not publicly funded infrastructure projects supporting bridge structures largely due to the lack of quantifiable quality assurance and quality controls. The development of computerized on-board drill rig monitoring systems and thermal integrity methods for auger cast piles removed many of the associated uncertainties. However, determination of the as-built grout volume confirming pile size remained problematic.

This study evaluated the construction records, inspector reports, thermal integrity assessments, and physical measurements from 1179 auger cast piles to identify potential problems in construction and/or inspection but more importantly to establish a reliable means to estimate the as-built, in-pile grout volume.

Recommendations stemming from the study findings promote the FHWA recommended best construction practices which state the drilling and grouting process should be performed without delay, without auger extraction prior to grouting, and making every effort to maintain a fully soil laden auger. Every effort should be made to reduce the frequency of re-stroking during auger cast pile construction which breaks the continuity of inspection data and potential harms/alters the lateral soil strength parameters.

The current FDOT specifications requiring manual pump stroke volumes and flow meter volumes to agree within 3% should be rigorously enforced. This may mean flow meters must maintain up-to-date calibration certifications. When both systems of measuring volume agree there is good correlation with the delivered truck volume.

The concept of an auger fill factor (AFF) was introduced to differentiate between the volume of grout that overflows to the ground surface and that which remains in the excavation. This makes as-placed grout volume the sum of the initial head volume, the incremental extraction volume, and the volume of the extracted auger which might be empty or completely filled with soil. Therein, the AFF is the ratio of the soil laden auger volume to a completely filled auger (ranging from 0.13, volume of the auger only, to 1.0, the volume of the cylindrical prism) for the auger in the excavation at the point of grout return. AFF estimations to the nearest 0.25 (e.g., 0.25, 0.5, 0.75, 1.0) will produce an acceptable level of accuracy for the final pile volume. Further, an inspector's booklet of common auger sizes and associated AFFs is recommended for auger cast pile installation.

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Executive Summary

Auger cast piles have historically been used for private industry applications but not publicly funded infrastructure projects supporting bridge structures largely due to the lack of quantifiable quality assurance and quality controls. The development of computerized on-board drill rig monitoring systems and thermal integrity methods for auger cast piles removed many of the associated uncertainties. However, determination of the as-built grout volume confirming pile size remained problematic.

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Chapter One: Introduction and Background

Continuous flight auger (CFA) piles are a subset of cast-in-place bored piles which include drilled shafts. CFA piles are commonly referred to as auger cast (ACP), augered-cast-in-place (ACIP), auger-pressure grouted, or screw piles (Brown et al., 2007). Where drilled shafts are excavated with augers of 3 or 4 flights, CFA pile equipment is easily distinguished from drilled shaft equipment by the full-length "continuous" auger used during construction. The continuous auger fills with soil during drilling, eliminating the need for mechanical or hydrostatic excavation support required when installing drilled shafts. Auger cast piles also have the benefit of being installed without significant noise, vibration, and ground movement associated with driven piles (Neely, 1991). In Florida, the ACIP, ACP, or auger cast pile terminology is most common.

To construct an auger cast pile, the full-length auger is drilled to the pile design depth in one continuous motion. As the auger advances, the flights fill with soil, providing support to the drilled excavation walls. The auger penetration rate and rotational speed should ideally promote an auger full of soil. Once the auger reaches the design depth, grout (cement, sand, and water mixture) is pumped using a positive displacement pump up through grout lines to the top of the drill rig and down through the hollow stem auger to the pile tip. The auger is then extracted at a controlled rate while grout is continuously pumped under pressure and a sufficient grout head is maintained. Once the auger is fully extracted and the grout is still highly fluid, a full-length steel reinforcement cage is lowered into the excavation.

The capacity of an auger cast pile is highly dependent on proper construction (McVay et al., 1994). Historically, auger cast piles have not been widely used for highway/transportation projects largely due to uncertainties surrounding grout volume monitoring, variation in construction practice, and limitations in integrity verification methods. The first step in the adoption of auger cast piles for transportation applications was the advent and widespread use of Automated Measuring Equipment (AME) capable of monitoring and recording virtually all aspects of the drilling and grouting processes. Recorded parameters now include the depth of the auger tip, the downward force on the auger (crowd), the rotational velocity of the auger (in rpm), auger stem inclination, grout pressure, and grout volume all recorded as a function of time. In many cases, the torque applied to the auger is also available via hydraulic pressure monitoring.

In 2017, the Deep Foundations Institute (DFI) conducted a pilot study in coordination with the Florida Department of Transportation (FDOT) to evaluate the use of auger cast piles for major public infrastructure projects. During the test pile installation, drill rig parameters and as-placed grout volumes were carefully monitored. After installation of the test piles, Thermal Integrity Profiling (TIP) was used to evaluate pile integrity. Load tests were performed, and one test pile was fully extracted to record as-built dimensions along the length of the pile (Marinucci & NeSmith, 2017). Since this pilot study, the use of auger cast piles to support bridges in the state of Florida has been approved for select projects with stringent quality assurance/inspection criteria.

The I-395 expansion project in Miami, FL is the largest infrastructure project to be supported on auger cast piles in Florida. This project is on-going and researchers at the University of South Florida have been receiving and cataloging all pertinent installation data. This chapter summarizes the DFI pilot study, other DFI efforts to collect ACP performance data, and the I-395 expansion project. The types of data retrieved are discussed with emphasis on what constitutes an acceptable minimum level of information.

1.1 Overview of Auger Cast Piles

Augered Cast-in-Place piles are a deep foundation element responsible for transferring large structural loads to the ground. They are also known as Continuous Flight Auger (CFA) piles, screw-piles, or auger cast piles due to the basic principle by which they are constructed. Unlike other geotechnical foundations, auger cast piles are drilled with an auger that is at least as long as the designed pile, providing excavation stability without any additional mechanical or hydrostatic support. Once drilled, grout is pumped through the hollow stem of the auger as it is slowly extracted from the excavation. Where in other countries concrete is used to fill the excavation, in Florida a high-slump grout (cement, sand, and water) is used rather than concrete to reduce potential clogging caused by coarse aggregate in the pumps, lines, and auger stem associated with the construction of auger cast piles.

1.2 Auger Cast Construction Techniques

Construction of auger cast piles begins with drilling an excavation to the pile design depth. As the continuous flight auger bit is advanced into the ground, the auger flights fill with soil cuttings that provide excavation support. Ideally, the auger is drilled to the design depth in one continuous motion with an auger rotational speed and penetration rate that promotes an auger full of soil without mining. Mining is the act of pulling the soil from the ground via an Archimedes screw action when rotation occurs without advancement. This causes decompression of the surrounding soil (reduction in lateral earth pressure) and can drastically change the initial soil conditions on which the design was based. (Neely, 1991) notes decompression occurring when the following relationship is satisfied:

$$\frac{np}{v} > 1 \tag{1.1}$$

where: *n = auger rotational speed (rpm)*
p = pitch of the auger flights
v = downward velocity of the auger (ft/min)

Once the pile design depth has been reached, grouting is to be started immediately (Brown et al., 2007). Before auger withdrawal begins, an initial grout head of 20ft or 20% of the pile length (whichever is greater) must be established for auger cast piles used as bridge foundations. For non-bridge foundations, an initial head of 5ft of grout or 10% of the pile length is required (FDOT REV 05-12-22, 2022). The grout head is established by pumping a grout volume equivalent to the theoretical pile volume corresponding to the initial head height.

NOTE: The term "head" in open channel flow or the fluid mechanics of pipe networks refers to the pressure state caused by fluid overburden expressed in units of feet (depth of water). In the case of ACP grouting, it denotes a theoretical volume of grout with a depth of 20ft (or 20% of the pile length) but only if the auger were not already occupying the same volume. The true pressure head *will be far more than the 20ft (or 20%) as the initial volume can only occupy the annulus around the soil-filled auger, portions of the auger that are not soil-laden, and regions where the grouting pressure pushes the sidewall outward radially. Hence, the initial head (in feet) extends far above the 20ft (or 20%) value.*

After the initial head is satisfied, the auger is then extracted while continuously pumping more volume in a section of the pile than the theoretical volume of that section, known as the grout factor, grout ratio, or overpour percentage. The grout factor is calculated by dividing the grout volume pumped by the theoretical cylindrical auger volume of that pile segment (typically 5ft increments). A grout volume greater than 115% of the theoretical grout volume is required for any given 5ft pile section below the Minimum Grout Return Depth (MGRD) and 100% above the MGRD (FDOT REV 05-12-22, 2022). The Grout Return Depth (GRD) is the depth of the auger tip when the grout is first seen returning to the ground surface. MGRD cannot be less than the initial grout head or the pile must be redrilled and regrouted to ensure this criterion is met. Upon completion of pile grouting, the steel reinforcement cage is lowered into the excavation while the grout is still highly fluid. The complete auger cast installation process can be seen in Figure 1.1.

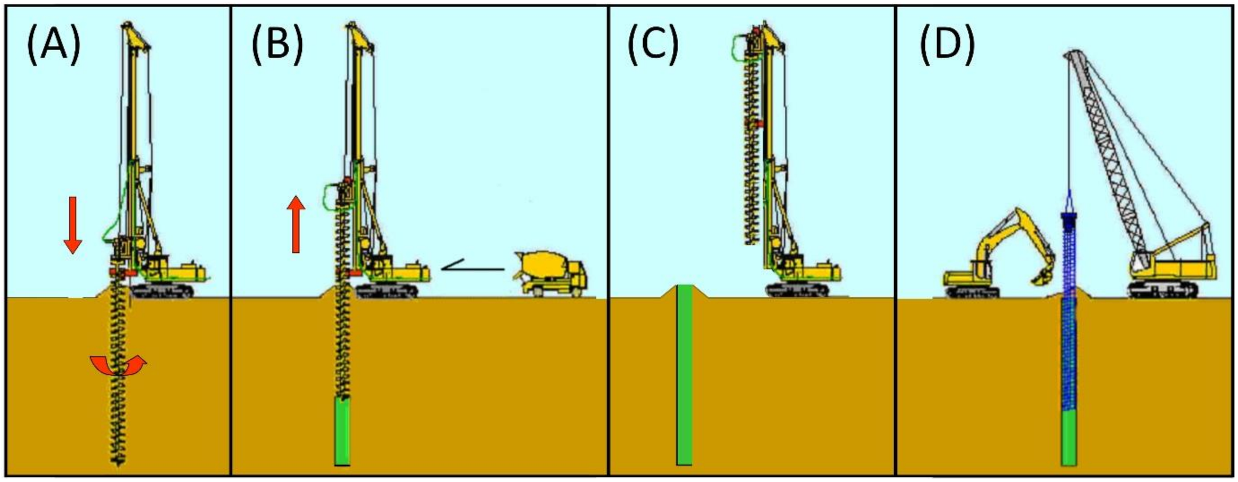


Figure 1.1 Auger cast pile construction process (a) drilling (b) grouting (c) pile completely grouted (d) cage placement; adapted from (Brown et al., 2007).

Many aspects of the installation process are monitored by Automated Measuring Equipment (AME) and a field engineer/inspector. Grout volume is an essential parameter monitored during installation. Accurate grout volumes are required to verify as-built pile dimensions and to complement other quality control methods such as Thermal Integrity Profiling (TIP). To account for grout volume during pile installation, the volume has been divided into four portions and defined as follows:

Volume 1: Priming Volume, grout volume required to prime grout pump, fill all hoses, and fill the full length of the hollow auger stem.

Volume 2: Initial Head Volume, grout head required by FDOT Standard Specifications for Road and Bridge Construction (i.e., 5ft of grout or 10% of pile length (whichever is greater) for non-bridge foundations or 20ft or 20% of pile length (whichever is greater) for bridge foundations).

Volume 3: Incremental Volume, volume pumped into the excavation as the auger is extracted to ensure uniform grout distribution along the length of the pile (i.e. 115% $\pi r^2 L_{segment}$). Volume 3 tracking ends at the moment of grout return. Grout return occurs when the grout has worked its way around the soil-laden auger flights and returns to the surface. The auger tip depth at this moment is the Grout Return Depth (GRD).

Volume 4: Finishing Volume, the grout volume pumped after grout return including that portion required to finish/fill the remaining pile volume and the grout overflowing onto the ground surface as grout continues to be pumped and the auger is extracted after the time of grout return.

To determine the completed pile volume based on these four volume portions, the simplified equation can be used:

$$\textit{Pile Volume} = \textit{Vol } 2 + \textit{Vol } 3 + \textit{Portion of Vol } 4 \tag{1.2}$$

Note that none of volume one, the volume to prime the grout pump/lines, is included in the final pile volume. The complete amount of volume 2 and volume 3 are counted in the pile volume, however, only a portion of volume 4 is counted. Recording of volume 4 begins at the point of grout return; when the grout is seen escaping at the ground surface from the excavation. However, distinguishing between in-pile or on-ground grout is difficult. Aside, grout is always flowing upward around the auger faster than auger extraction. This is due to the minimum grout factor requirement. Hence at the time of grout return, a portion of Vol 3 resides in or around the auger flights with soil cuttings.

To quantify the in-pile portion of Vol 4, the volume of the auger and soil retained on the auger flights must be replaced by grout. The maximum contribution from Vol 4 to in-pile volume is therefore the product of the cross-sectional area of the auger (πr^2) and the return depth (GRD). This assumes a completely soil-filled auger forming a perfect cylindrical prism. When partially filled, the fraction of the perfect cylindrical volume that remains is denoted as the Auger Fill Factor (AFF). The AFF is calculated as follows:

$$\textit{AFF} = (\textit{Auger Vol.} + \textit{Soil Vol.}) / \textit{Nominal Cylinder Vol.} \tag{1.3}$$

The nominal cylinder volume refers to a full cylinder with the same outer diameter as the auger and a length equivalent to the return depth. The AFF represents the amount of grout volume that needs to be added which cannot be tracked and is estimated to be only as large as the volume of the soil cuttings and the steel auger. A visual representation of the portion of Vol 4 that is of concern can be seen in Figure 1.2.

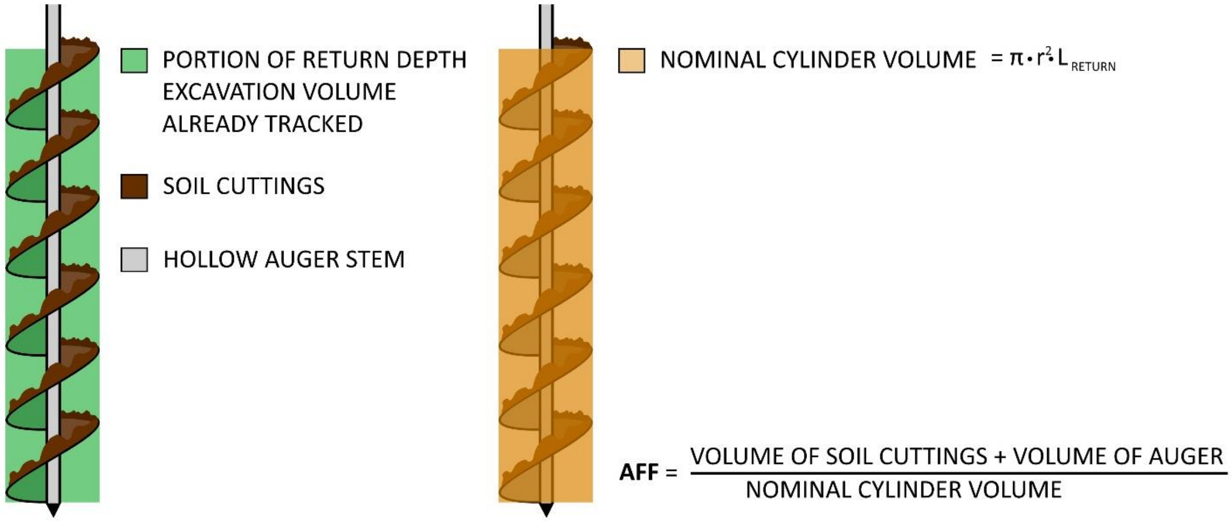


Figure 1.2 Visual representation of AFF and Vol 4 (Mee, 2022)

Once the AFF is estimated, it can be used to calculate the in-pile portion of Vol 4 that is contributing to the final pile volume with the following equation where r is the auger radius:

$$Portion\ of\ Vol\ 4 = AFF\ \pi r^2 L_{return} \tag{1.4}$$

When substituted into Eq. (1.2) the resulting equation of the final pile volume can be obtained:

$$Pile\ Volume = Vol\ 2 + Vol\ 3 + AFF\ \pi r^2 L_{return} \tag{1.5}$$

At the onset of the study, the state of practice for determining total pile volume ranged from assigning all pumped grout to the pile volume to assuming a full auger (AFF =1).

Monitoring the grout volume placed during the installation of auger cast piles is one of the most important parameters for evaluating pile integrity. An accurate pile volume ensures the pile was sufficiently grouted and knowing the grout volume pumped as a function of depth provides a look at the grout distribution throughout the pile. A section of a pile with an insufficient grout volume can be identified during installation and remediation measures can be taken. To remediate an under-grouted section, the pile must be re-drilled and re-grouted (Piscsalko & Likins, 2003). The pile must be re-drilled to at least 15ft below the tip of the auger where a grouting interruption or pressure loss occurred (FDOT REV 05-12-22, 2022). Currently, the FDOT requires a grout factor of 1.15 below the MGRD and 1.00 above the MGRD. Neely (1991) demonstrated how the grout factor can affect the load bearing capacity of an auger cast pile. Figure 1.3 shows the load test results of four 16in diameter auger cast piles with various grout factors. This shows a general trend of increased capacity with an increased grout factor, but in one case a higher grout factor (Pile A; L=39ft) resulted in a lower capacity relative to the next lowest grout factor (Pile B; L=47ft). This was most likely due to the shorter pile length that could not develop as much grout pressure. Interestingly, this is similar to post-grouted end bearing improvements that were originally shown to be proportional to grout volume but were later shown to be more closely related to the achieved grout pressure.

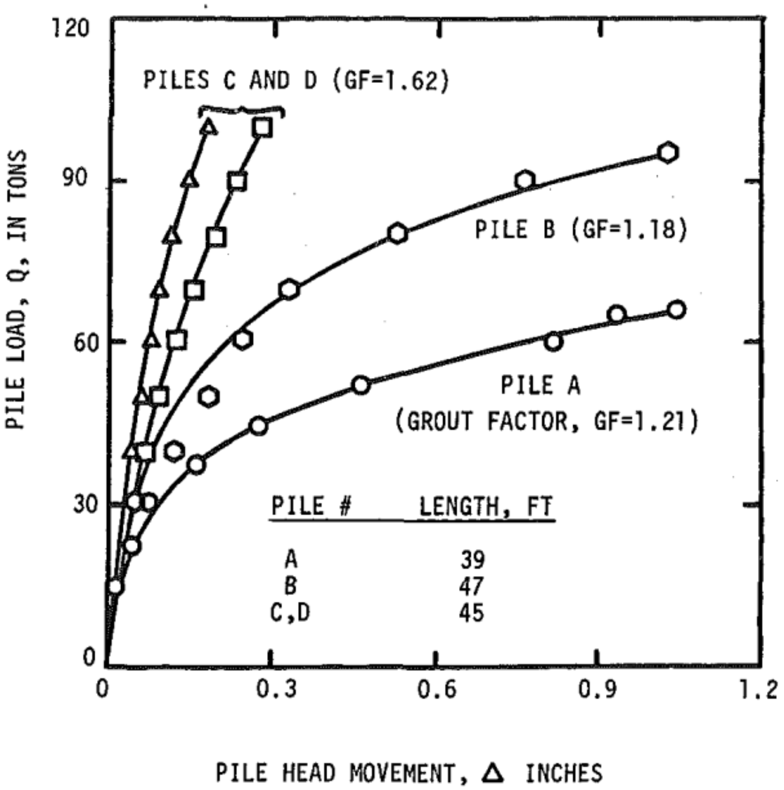


Figure 1.3 Load test data from four auger cast piles with varying grout factors (Neely, 1991)

1.3 Grout Pump

Grout can either be mixed off-site by a ready-mix supplier and delivered in standard 8CY concrete trucks or mixed on-site in a batch plant. Once on-site, grout is fed into the hopper of a grout pump. Two examples of grout pumps used for auger cast pile installation can be seen in Figure 1.4.

Figure 1.4 Two examples of grout pumps used during auger cast installation; left (Brown et al., 2007) and right (Marinucci & NeSmith, 2017)

Typical grout pumps used are double-acting positive displacement pumps capable of producing grout pressures of 350psi. The grouting pump feeds 2.5 to 4in diameter lines that lead to the hollow stem auger (Brown et al., 2007). The grout flows down the hollow stem auger and begins filling the pile excavation as the auger is continuously extracted. Double-acting positive displacement pumps make use of both forward and reverse strokes of the piston to displace grout volume. On both strokes, grout is pulled into one side of the cylinder and displaced out the other side. Four check valves ensure grout is properly moved during both the forward and reverse pump strokes. Figure 1.5 shows a general diagram of a double-acting positive displacement pump as well as the movement of grout through the pump during both the forward and reverse pump strokes.

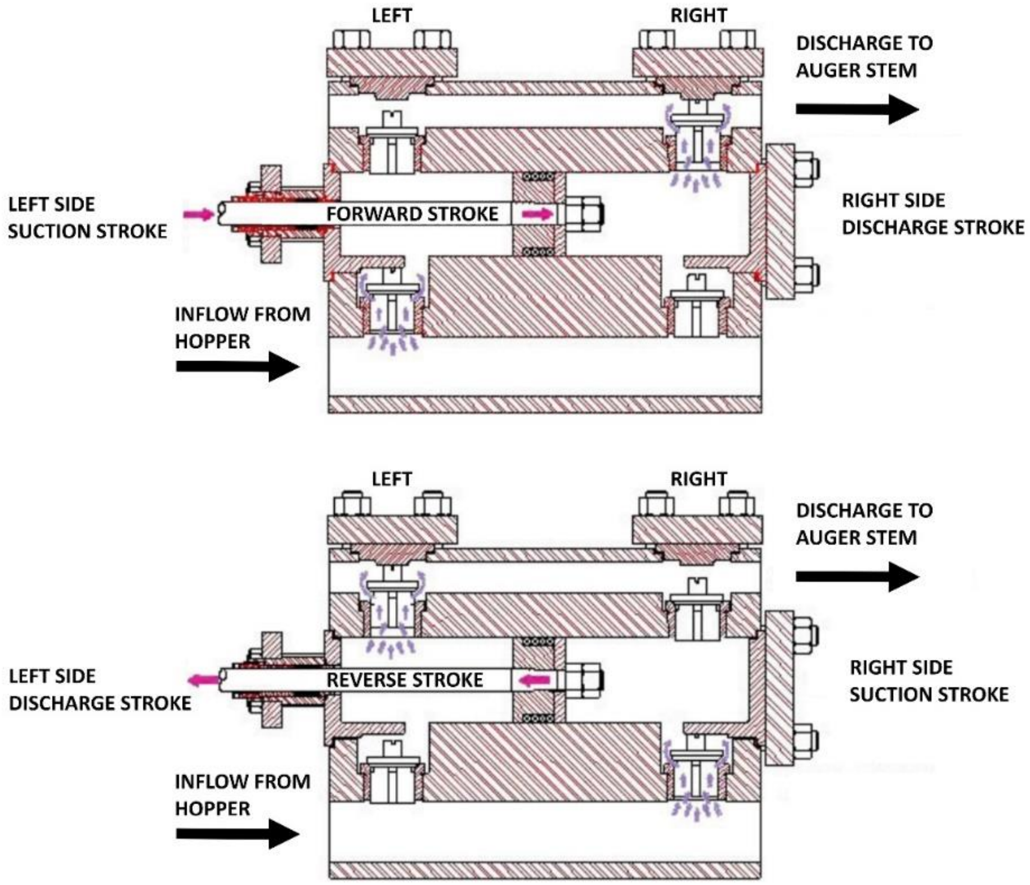


Figure 1.5 General diagram of a double-acting positive displacement (Tackett et al., 2008); used and adapted with permission.

Grout pumps are calibrated by pumping several strokes of grout into a 55-gallon drum on-site. Before pumping, the drum diameter and internal height are measured. After pumping, the distance from the top of the drum to the top of the pumped grout is measured. The calculated grout volume in the drum is divided by the number of strokes required to achieve that volume, providing a cuft/stroke pump calibration constant. Grout pumps are calibrated following the *Florida Method of Test for Displacement Grouting Pump Calibration with a Cylindrical Container – Designation FM 5-612* (FDOT, 2016). Figure 1.6 shows a grout pump calibration being performed.

Figure 1.6 Grout pump calibration using 55-gallon drum (Castellanos, 2015)

With a properly calibrated grout pump, the volume of grout pumped during the construction of an auger cast pile can be monitored by counting pump strokes. Pump strokes are typically counted audibly or by maintaining a foot on the grout line and feeling for the expanding and bucking grout line. The number of pump strokes are typically recorded on 5ft intervals of auger extraction starting from the pile tip to the ground surface. Pump strokes per 5ft segment of a pile provide an initial view of the grout distribution along the pile length.

1.4 Magnetic Flow Meter

An in-line magnetic flow meter can also be installed to provide a complimentary method of tracking grout volume during auger cast pile installation. This flow meter produces a magnetic field around the internal circular cross-section where grout flows. The fluid flow induces a voltage, measured by Automated Measuring Equipment (AME), which is proportional to the average flow velocity (Brown et al., 2007). The flow rate is then calculated using the known cross-sectional area of the flow meter and the measured grout velocity. The flow rate is integrated over time giving the cumulative grout volume. An in-line flow meter used during the construction of auger piles can be seen in Figure 1.7.

Figure 1.7 In-line magnetic flow meter (Brown et al., 2007).

Magnetic flow meters are capable of measuring the velocity of difficult fluids like grout and have no moving mechanical parts, requiring low maintenance (Omega, 2018). A general diagram of the components and operating principles of an in-line electromagnetic flow meter can be seen in Figure 1.8.

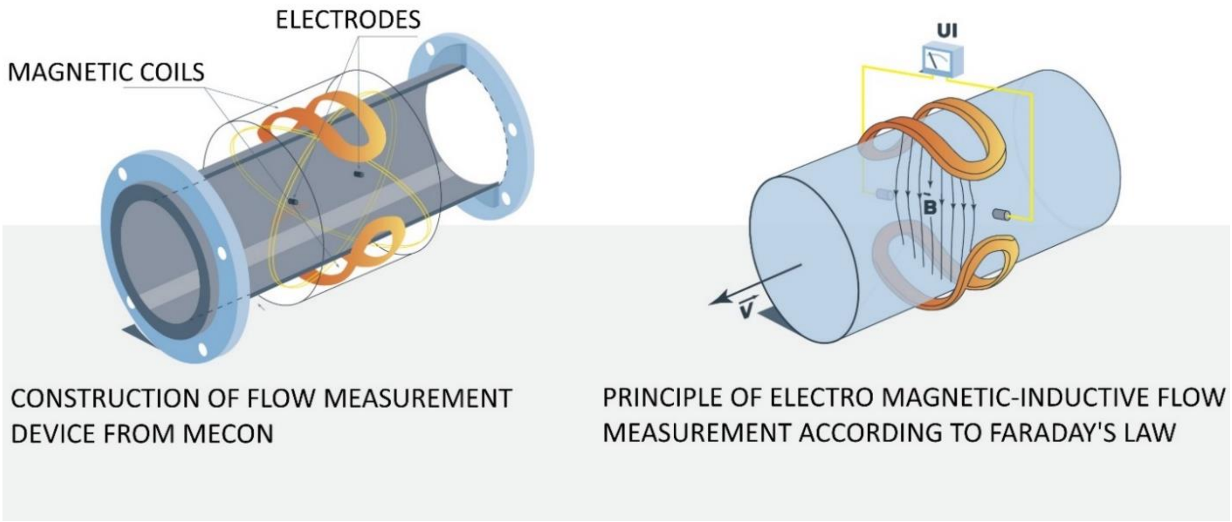


Figure 1.8 Diagram of an in-line electromagnetic flow meter (MECON GmbH); used and adapted with permission.

The electrodes, in direct contact with the flowing grout, measure a voltage that is proportional to the velocity of the flowing fluid based on Faraday's law of induction (Hofmann, 2003). As the grout moves faster, the measured voltage across the electrodes increases. Equation 1.6 describes Faraday's Law where measured voltage is proportional to flow velocity:

$$U_i = (v \text{ x } B) \cdot L \tag{1.6}$$

where: U_i = *induced voltage vector*
B = *induction vector*
L = *length of a conductor moving through a magnetic field*
v = *fluid velocity vector*

Traditional magnetic flow meters are designed for large volumes of continuous flow. Positive displacement pumps like those used during auger cast pile installation create a pulsed flow condition. It has been demonstrated that a magnetic flow meter with a manufacturer-specified volume accuracy of +/- 0.25% under steady flow conditions has a volume accuracy of +/- 2% under pulsed flow conditions (Likens et al., 1998).

1.5 Thermal Integrity Profiling (TIP)

Thermal Integrity Profiling (TIP) was developed to take advantage of the exothermic nature of curing concrete or grout to gain insight into the integrity of foundation elements. This integrity evaluation method was originally developed for use in drilled shafts (Mullins, 2010) and was later shown to be suitable for auger cast piles (Mullins & Johnson, 2017). However, it is important to note the differences between the two foundation elements. Drilled shafts tend to have larger diameters than auger cast piles (3 to 15ft in diameter compared to 12 to 30in, respectively). Concrete is placed in a drilled shaft through a tremie pipe after installation of the reinforcement cage in the open excavation supported by mechanical or hydrostatic means. Alternatively, auger cast piles are constructed using grout without coarse aggregates. Grout is pumped through grouting lines and down the hollow stem of the continuous flight auger after drilling to the design depth. Shortly after the excavation is fully grouted, the auger cast reinforcement cage is lowered down through the still highly fluid grout.

In both drilled shafts and auger cast piles, TIP can be performed by either lowering an instrumented probe down through access tubes installed along the length of the cage or by using thermal wires that are affixed to the cage and cast into the foundation element. Figure 1.9 shows a probe instrumented with four infrared sensors being lowered into the access tubes of an auger cast pile while a rotary encoder assembly recorded the depth of the probe. The probe-based procedure would typically be performed once at the time of near peak temperature (e.g. 24 to 72hrs after casting) (Mullins & Johnson, 2017).

Figure 1.9 Infrared sensor probe being lowered into an auger cast pile access tube (Mullins & Johnson, 2017)

Thermal wires can also be tied to the reinforcement cage, allowing for continuous data collection over multiple days at the expense of not recovering the thermal wires after testing. The thermal wires most commonly have temperature sensors spaced at 1ft intervals. While the number of thermal wires installed may vary, four thermal wires are generally installed in auger cast piles in a north-south-east-west configuration, with each thermal wire 90 degrees from the last. Figure 1.10 shows thermal wires tied along the length of an auger cast reinforcement cage.

Figure 1.10 Thermal wires (yellow) tied along the length of an auger cast reinforcement cage

The modeled temperature distribution of a perfectly cylindrical foundation element can be seen in Figure 1.11. The highest temperature is found at the center of the pile and decreases radially as heat is transferred to the surrounding soil. The vertical temperature distribution is ideally uniform expect for at the top and bottom of the shaft, where additional heat is being transferred to the surrounding air at the pile top and the additional soil at the pile tip. Significant temperature increases or decreases at a specific pile depth may indicate bulges or necks/inclusions in the pile, respectively. TIP can also be used to indicate reinforcement cage misalignment when two opposing thermal wires deviate in opposite directions from the average temperature profile (Mullins & Johnson, 2016).

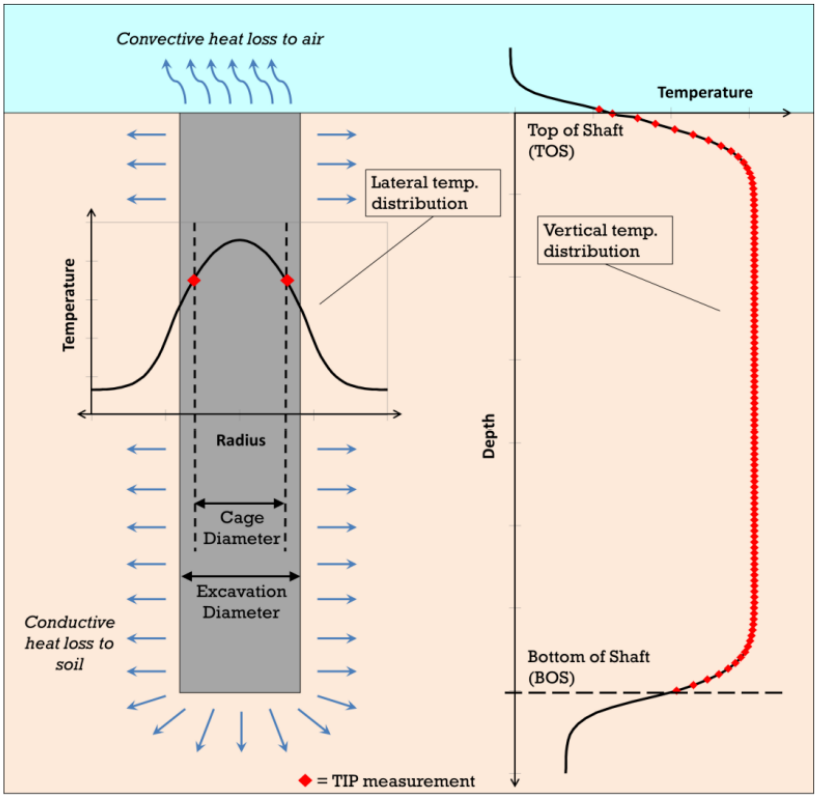


Figure 1.11 Temperature distribution of a perfectly cylindrical pile (Mullins & Johnson, 2016)

The radius of a drilled shaft or ACIP pile can be predicted from the measured temperature using an average shaft (or pile) temperature corrected for end effects and the overall shaft (or pile) volume converted to an average radius of a cylindrical prism with a length that of the shaft (or pile). This analysis produces a time, mix design, cage diameter, and shaft diameter dependent temperature to radius (T-R) relationship. For larger diameter shafts (>3ft in diameter) a linear temperature to radius is relationship is computed that is valid for radii within the linear region of the true hyperbolic T-R relationship. Figure 1.12 shows how the true hyperbolic T-R relationship changes for small and large diameter concrete elements.

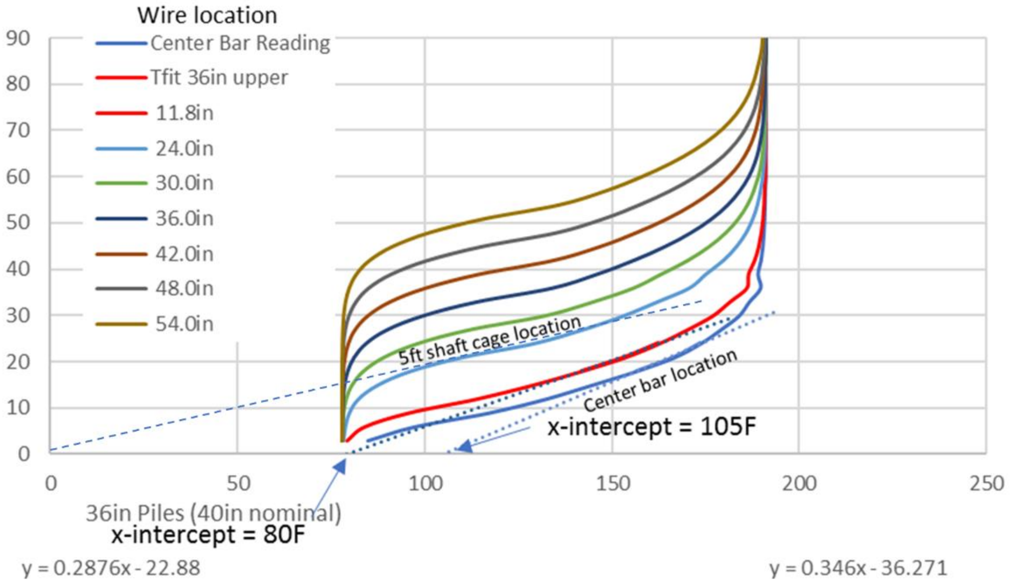


Figure 1.12 Relationship between shaft size and temperature for a given cage position (Johnson, 2014)

When the linear T-R is struck through the origin, called the Tzero method, there is good agreement when using cage temperature measurements for large elements. For cage-based measurements from smaller elements (≤3ft diam) or when the measurement location is near the center of the element, the X-intercept is set at the coordinate (Tsoil, 0). This linear relationship is called the Tsoil method and was shown to better predict radius is small elements like that shown in Figure 1.13 from Mullins, et al. (2017). Figure 1.14 shows the error associated with using the Tzero method on 2ft diameter piles based on actual pile measurements from an extracted pile.

The motivation for this study resulted from the inability to accurately predict pile size from thermal integrity assessments due to uncertain pile volumes and to make ACIP piles are more reliable FDOT bridge foundation element. However, thermal assessments only highlighted the inability to know the precise pile volume; there has always been the need to know this information before ACIP piles could be taken to the next level as bridge foundation elements.

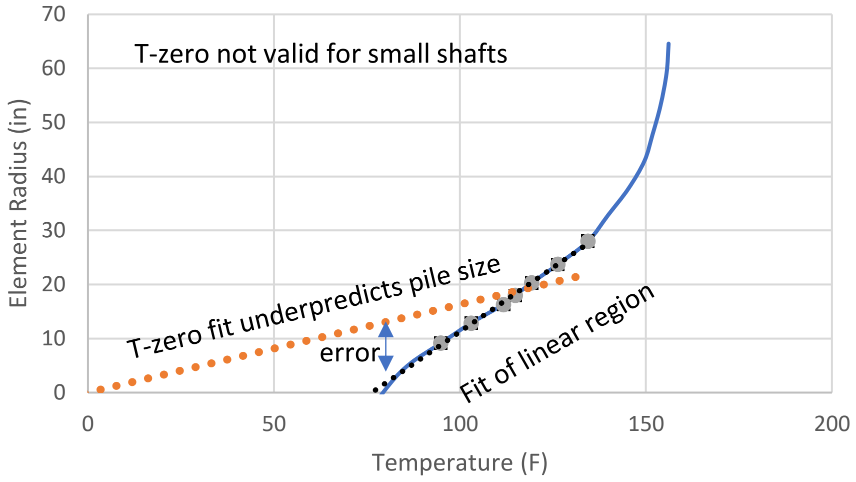


Figure 1.13 Tsoil method better suited for small elements.

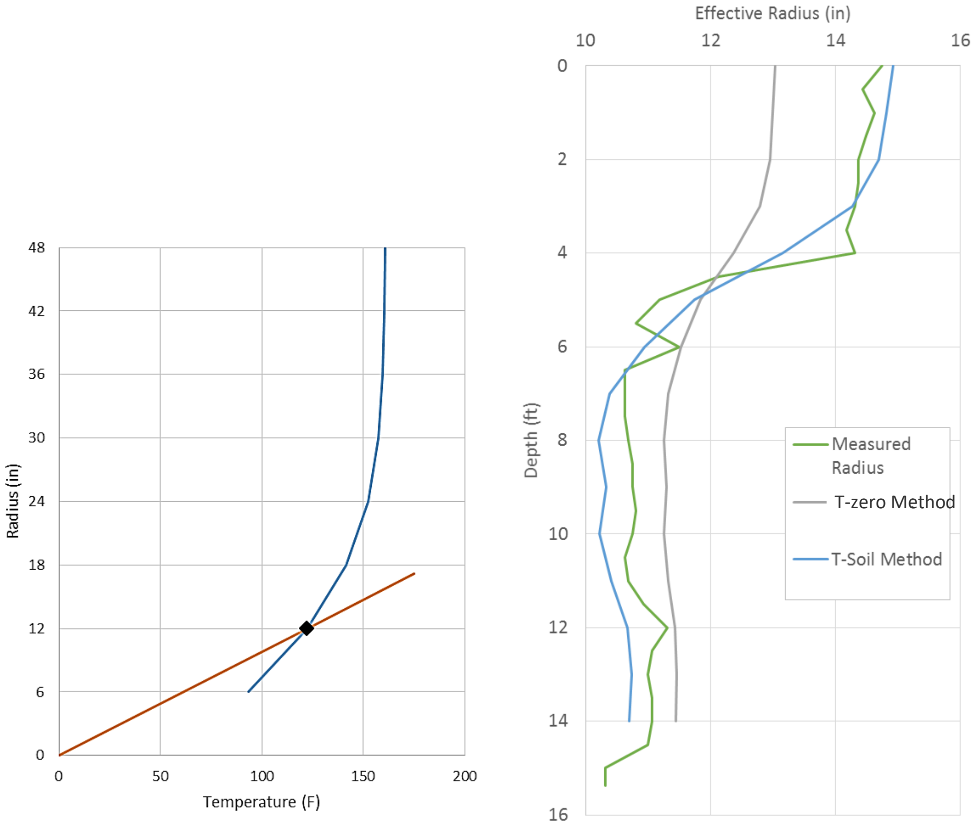


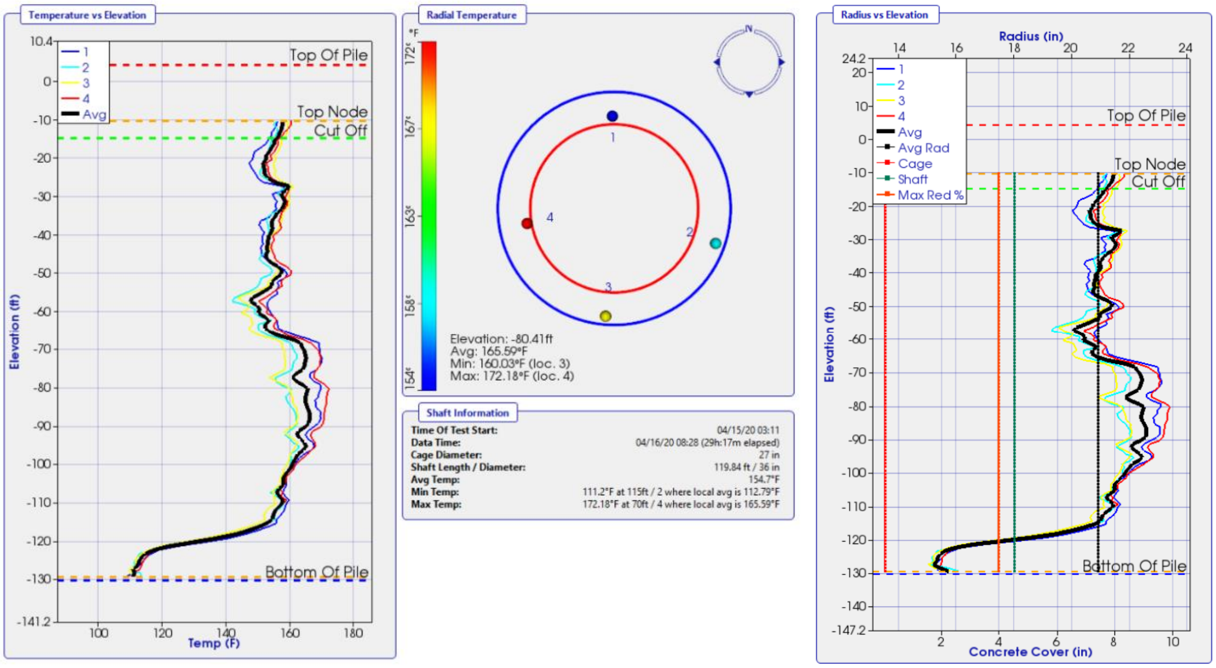
Figure 1.14 Effect of Tsoil and Tzero methods on radius prediction

Chapter Two: Previously Collected Data

As the performance of auger cast piles is highly dependent on pile construction, installation monitoring is required for integrity evaluation and certification of an auger cast pile. This chapter provides an overview of the types of installation data recorded during auger cast pile installation. This installation data includes (1) Thermal Integrity Profiling (TIP) data, (2) Automated Measuring Equipment (AME) data, (3) field installation logs, and (4) as-built dimensions recorded at the cut-off elevation. As part of this study, auger cast installation data has been collected from a pilot study conducted by the Deep Foundations Institute (DFI) and from the ongoing I-395 expansion project in Miami, FL. A summary of the previously collected data from these two projects is presented as well.

2.1 Thermal Integrity Profiling (TIP) Data

The TIP data received from the I-395 expansion project came in the form of raw TIP data or TIP reports. The TIP reports summarize the results of the TIP testing and provide interpretations of the as-built pile dimensions based on the temperature to radius (T-R) correlation. An example temperature profile, TIP wire orientation, and interpreted pile radius profile are provided in Figure 2.1.

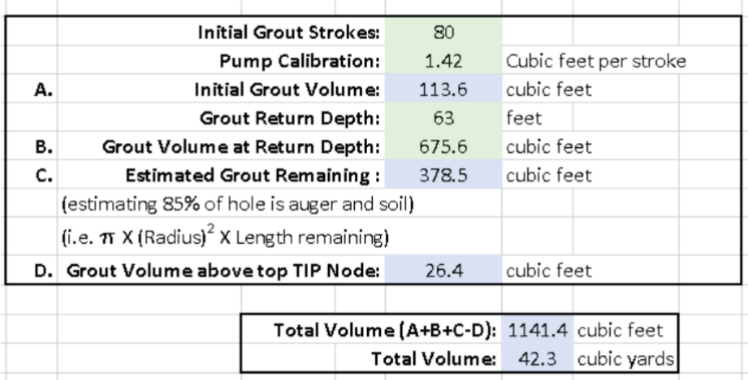


Elevation: -80.41ft
Avg: 165.59°F
Min: 160.03°F (loc. 3)
Max: 172.18°F (loc. 4)

Time Of Test Start: 04/15/20 03:11
Data Time: 04/16/20 08:28 (29h:17m elapsed)
Cage Diameter: 27 in
Shaft Length / Diameter: 119.84 ft / 36 in
Avg Temp: 154.7°F
Min Temp: 111.2°F at 115ft / 2 where local avg is 112.79°F
Max Temp: 172.18°F at 70ft / 4 where local avg is 165.59°F

Figure 2.1 Temperature profile (left), thermal wire orientation (center), and interpreted pile radius profile (right)

The TIP reports also summarize the grout volumes recorded during pile installation. These grout volumes are divided into volumes A, B, C, and D. Volumes A, B, and C correspond to volumes 2, 3, and the in-pile portion of Vol 4 (defined in Section 1.2), respectively. Briefly, volume 2 is the initial head volume established before auger removal, volume 3 is the incremental volume recorded during auger extraction, and the in-pile portion of Vol 4 is the estimated volume required to complete the pile at the point of grout return. These volumes are used to calculate the total pile volume. Figure 2.2 shows an example summary of recorded pile volumes within the TIP reports. Note an AFF value of 85% was assumed but not explicitly defined as such.



	Initial Grout Strokes:	80	
	Pump Calibration:	1.42	Cubic feet per stroke
A.	**Initial Grout Volume:**	113.6	cubic feet
	Grout Return Depth:	63	feet
B.	**Grout Volume at Return Depth:**	675.6	cubic feet
C.	**Estimated Grout Remaining :**	378.5	cubic feet
	(estimating 85% of hole is auger and soil)		
	(i.e. π X $(\text{Radius})^2$ X Length remaining)		
D.	**Grout Volume above top TIP Node:**	26.4	cubic feet

Total Volume (A+B+C-D):	1141.4	cubic feet
Total Volume:	42.3	cubic yards

Figure 2.2 Example grout volume summary provided in a TIP report

Volume D, which is not defined in Section 1.2, is that portion of the overall pile volume that resides above the top-most thermal sensor and which cannot be included in the TIP evaluation algorithms. This volume is estimated to be the nominal pile size converted to cross-sectional area times the depth distance between the ground surface (where grout return is documented to occur) and the location of the topmost thermal sensor. This estimation does not account for pile oversizing which is expected especially at near-surface locations where auger wobble is often experienced. Hence, by subtracting a smaller than actual volume (D), a larger placed volume is assumed, and the temperature to radius conversion will then overestimate the actual pile size, one source of error.

2.2 Automated Measuring Equipment (AME) Data

During the construction of auger cast piles, the drill rigs are equipped with Automated Measuring Equipment (AME) to record data from various transducers. This data provides essential information about the drilling and grouting operations. The AME data received from the I-395 expansion project has a recording frequency of 1Hz and includes the following drilling parameters:

1. Time (MM/DD/YYYY hh:mm:ss)
2. Duration (minutes)
3. Gear Box Rotational Speed (rpm)
4. Penetration Rate (ft/min)
5. Depth (ft)
6. Gear Box Pressure (psi)
7. Torque (ft-lbs)
8. Crowd Pressure (psi)
9. Thrust (lbs)

Similarly, the AME grouting data includes:

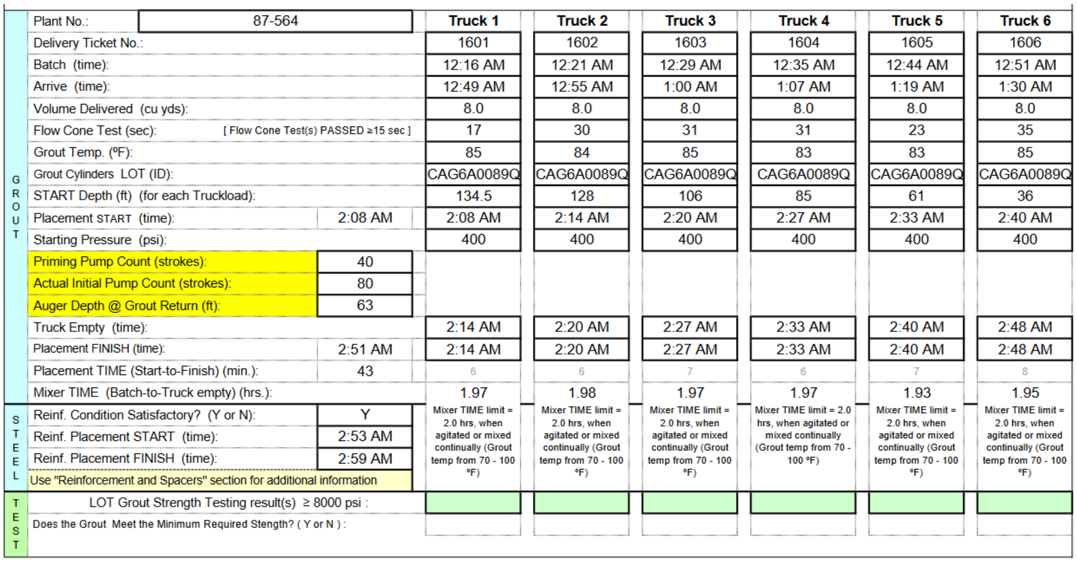
1. Time (MM/DD/YYYY hh:mm:ss)

2. Duration (minutes)
3. Gear Box Rotational Speed (rpm)
4. Withdrawal Rate (ft/min)
5. Depth (ft)
6. Flow Meter Grout Flow (cfm)
7. Flow Meter Grout Volume (cf)
8. Grout Factor (Flow Meter)
9. Grout Pressure (psi)
10. Pump Stroke Count
11. Pump Stroke Flow Rate (cfm)
12. Pump Stroke Volume (cf)
13. Grout Factor (Strokes)
14. Cumulative GF Stroke
15. Cumulative GF Meter

The AME installation data is stored as an excel workbook (.xlsx) with two sheets, one to store the drilling data and one to store data from the grouting operation. The AME data provides a means of comparing grout volume measured by the magnetic flow meter and grout volume calculated with the number of pump strokes.

2.3 Field Installation Logs

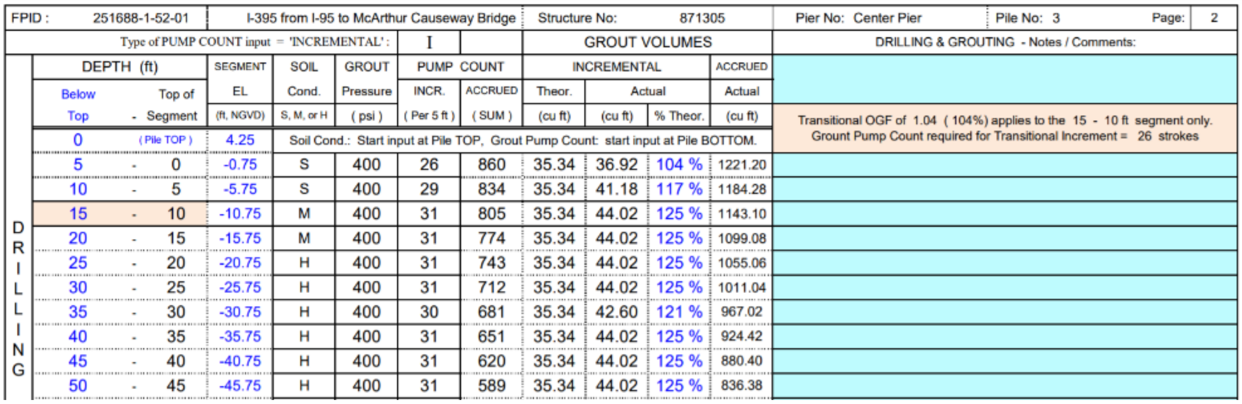
During pile installation, inspection values are recorded in an installation log, culminating in a five-page pile installation document. A few key portions are identified starting with the truck information on page 1 of the installation log, seen in Figure 2.3. This installation log was pulled from Bridge 8 – Center Pier – Pile 3. The grout volume per truck and the time of batching, arrival, placement, and completion (truck empty) are provided. This data provides an overview of grout volume and a general timeline of the drilling and grouting operation.



GROUT	Plant No.:	87-564	Truck 1	Truck 2	Truck 3	Truck 4	Truck 5	Truck 6
	Delivery Ticket No.:		1601	1602	1603	1604	1605	1606
	Batch (time):		12:16 AM	12:21 AM	12:29 AM	12:35 AM	12:44 AM	12:51 AM
	Arrive (time):		12:49 AM	12:55 AM	1:00 AM	1:07 AM	1:19 AM	1:30 AM
	Volume Delivered (cu yds):		8.0	8.0	8.0	8.0	8.0	8.0
	Flow Cone Test (sec):	[Flow Cone Test(s) PASSED ≥15 sec]	17	30	31	31	23	35
	Grout Temp. (ºF):		85	84	85	83	83	85
	Grout Cylinders LOT (ID):		CAG6A0089Q	CAG6A0089Q	CAG6A0089Q	CAG6A0089Q	CAG6A0089Q	CAG6A0089Q
	START Depth (ft) (for each Truckload):		134.5	128	106	85	61	36
	Placement START (time):	2:08 AM	2:08 AM	2:14 AM	2:20 AM	2:27 AM	2:33 AM	2:40 AM
	Starting Pressure (psi):		400	400	400	400	400	400
	Priming Pump Count (strokes):	40						
	Actual Initial Pump Count (strokes):	80						
	Auger Depth @ Grout Return (ft):	63						
	Truck Empty (time):		2:14 AM	2:20 AM	2:27 AM	2:33 AM	2:40 AM	2:48 AM
	Placement FINISH (time):	2:51 AM	2:14 AM	2:20 AM	2:27 AM	2:33 AM	2:40 AM	2:48 AM
	Placement TIME (Start-to-Finish) (min.):	43	6	6	7	6	7	8
	Mixer TIME (Batch-to-Truck empty) (hrs.):		1.97	1.98	1.97	1.97	1.93	1.95
STEEL	Reinf. Condition Satisfactory? (Y or N):	Y	Mixer TIME limit = 2.0 hrs, when agitated or mixed continually (Grout temp from 70 - 100 ºF)	Mixer TIME limit = 2.0 hrs, when agitated or mixed continually (Grout temp from 70 - 100 ºF)	Mixer TIME limit = 2.0 hrs, when agitated or mixed continually (Grout temp from 70 - 100 ºF)	Mixer TIME limit = 2.0 hrs, when agitated or mixed continually (Grout temp from 70 - 100 ºF)	Mixer TIME limit = 2.0 hrs, when agitated or mixed continually (Grout temp from 70 - 100 ºF)	Mixer TIME limit = 2.0 hrs, when agitated or mixed continually (Grout temp from 70 - 100 ºF)
	Reinf. Placement START (time):	2:53 AM						
	Reinf. Placement FINISH (time):	2:59 AM						
	Use "Reinforcement and Spacers" section for additional information							
TEST	LOT Grout Strength Testing result(s) ≥ 8000 psi :							
	Does the Grout Meet the Minimum Required Stength? (Y or N) :							

Figure 2.3 Bridge 8 – Center Pier – Pile 3 example grout truck log (page 1 of 3)

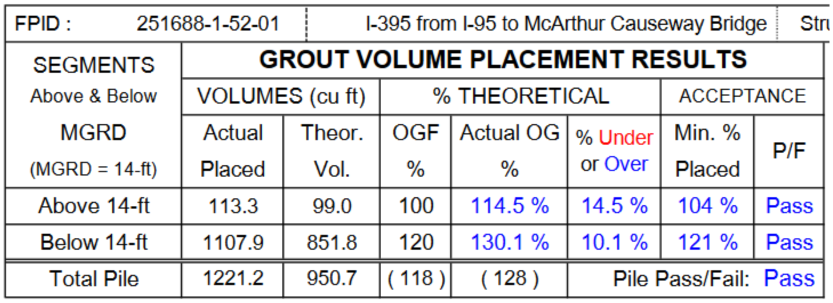
Page 2 of the installation log provides the incremental volumes placed for each 5ft section of the pile, seen in Figure 2.4. This figure shows the last 50ft of grouting or the 50ft of the pile below the ground surface elevation. It should be noted that the data-sheet is populated from the bottom up as the auger is extracted from deeper to shallower depths. In this case, 836cuft of grout had been placed when the auger tip had risen to a depth of 50ft. The incremental grout volume for each 5ft section was calculated by multiplying the corresponding number of pump strokes by the pump calibration coefficient (cuft/stroke). In this example, the calibration coefficient was 1.42cuft/stroke. The grout volume pumped for each 5ft section was compared to the theoretical volume required for a full 5ft cylindrical pile segment, given in the "*% Theor.*" column.



FPID :	251688-1-52-01	I-395 from I-95 to McArthur Causeway Bridge				Structure No:	871305					Pier No: Center Pier · Pile No: 3 · Page: 2
Type of PUMP COUNT input = 'INCREMENTAL' :					I		GROUT VOLUMES					DRILLING & GROUTING - Notes / Comments:
	DEPTH (ft)		SEGMENT	SOIL	GROUT	PUMP COUNT		INCREMENTAL			ACCRUED	
	Below Top	- Top of Segment	EL (ft, NGVD)	Cond. S, M, or H	Pressure (psi)	INCR. (Per 5 ft)	ACCRUED (SUM)	Theor. (cu ft)	Actual (cu ft)	% Theor.	Actual (cu ft)	Transitional OGF of 1.04 (104%) applies to the 15 - 10 ft segment only. Grount Pump Count required for Transitional Increment = 26 strokes
	0	(Pile TOP)	4.25	Soil Cond.: Start input at Pile TOP, Grout Pump Count: start input at Pile BOTTOM.								
	5	- 0	-0.75	S	400	26	860	35.34	36.92	104 %	1221.20	
	10	- 5	-5.75	S	400	29	834	35.34	41.18	117 %	1184.28	
DRILLING	15	- 10	-10.75	M	400	31	805	35.34	44.02	125 %	1143.10	
	20	- 15	-15.75	M	400	31	774	35.34	44.02	125 %	1099.08	
	25	- 20	-20.75	H	400	31	743	35.34	44.02	125 %	1055.06	
	30	- 25	-25.75	H	400	31	712	35.34	44.02	125 %	1011.04	
	35	- 30	-30.75	H	400	30	681	35.34	42.60	121 %	967.02	
	40	- 35	-35.75	H	400	31	651	35.34	44.02	125 %	924.42	
	45	- 40	-40.75	H	400	31	620	35.34	44.02	125 %	880.40	
	50	- 45	-45.75	H	400	31	589	35.34	44.02	125 %	836.38	

Figure 2.4 Bridge 8 – Center Pier – Pile 3 example incremental volume log (page 2 of 3)

During installation, piles are required to be over-grouted to ensure as-built pile dimensions and integrity. The specifications for over-grouting are different for the sections of a pile above and below the Minimum Grout Return Depth (MGRD). A minimum grout volume equal to 115% of the theoretical volume must be placed below the MGRD to the pile tip. Above the MGRD, 100% of the theoretical volume must be placed. If the placed grout volume does not meet these requirements, the pile must be re-grouted from a point 10ft below the under-grouted section or the bottom of the pile if required. Page 3 of the installation log summarizes these over-grouting percentages (Figure 2.5) and assigns a pass or fail accordingly. It should be noted that the installation log shown in Figure 2.5 requires an over-grouting factor (OGF) of 120% below MGRD, more than the currently required 115%.



FPID : 251688-1-52-01	I-395 from I-95 to McArthur Causeway Bridge					Stru	
SEGMENTS	GROUT VOLUME PLACEMENT RESULTS						
Above & Below	VOLUMES (cu ft)		% THEORETICAL			ACCEPTANCE	
MGRD (MGRD = 14-ft)	Actual Placed	Theor. Vol.	OGF %	Actual OG %	% Under or Over	Min. % Placed	P/F
Above 14-ft	113.3	99.0	100	114.5 %	14.5 %	104 %	Pass
Below 14-ft	1107.9	851.8	120	130.1 %	10.1 %	121 %	Pass
Total Pile	1221.2	950.7	(118)	(128)	Pile Pass/Fail:		Pass

Figure 2.5 Bridge 8 – Center Pier – Pile 3 example grout volume placement results (page 3 of 3)

2.4 Drop Hammer Testing

Drop hammer dynamic load testing was used to verify load bearing capacity of installed piles. Applied Foundation Testing (AFT) was slated to perform drop hammer testing on 5% of the planned 2000 production piles in the Miami I-395 expansion project. Figure 2.6 shows the drop hammer dynamic test device built by AFT. This testing method conforms to the "Standard Test Method for High-Strain Dynamic Testing of Deep Foundations," ASTM D4945.

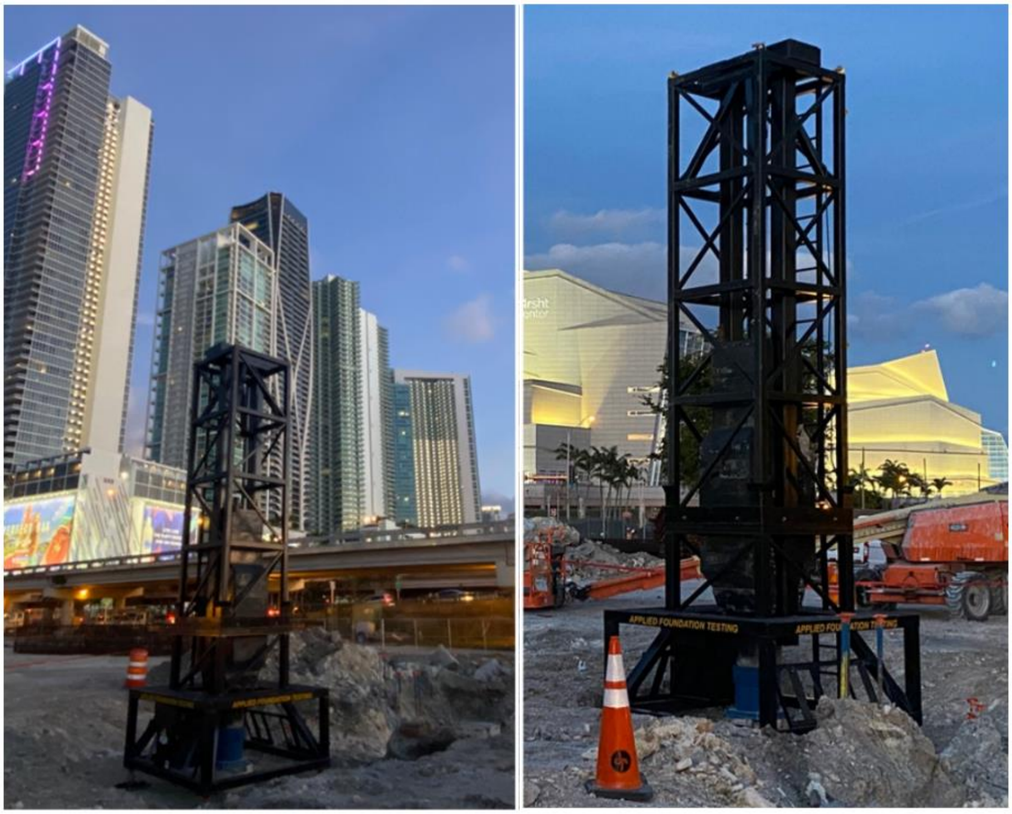


Figure 2.6 Drop hammer testing performed by Applied Foundation Testing (AFT, 2020)

While drop hammer testing data has been received and catalogued for select piles, it is not currently being used in the analysis of as-built grout volume. Furthermore, the data summaries for each pier in the appendices do not include the received drop hammer load testing results.

2.5 As-built Measurements at Cut-off Elevation

During the pilot study performed by the Deep Foundations Institute (DFI) in 2016, a pile was extracted after installation to take diameter and circumference measurements at 1ft increments along the length of the pile. While desirable in a research setting, this is not realistic for production piles. Instead, as-built dimensions were taken at the cut-off elevation, once the pile group was excavated and the pile tops are exposed.

To understand the cut-off elevation, it is important to note that auger cast piles are constructed to the existing ground surface elevation or established working platform elevation. After installation, the fill surrounding a pile group is excavated for the pier footing, as it extends below the ground surface elevation. The grout making up a pile above the cut-off elevation is chipped away to expose the steel reinforcement which is used to tie into the pier footing. The elevation of the new pile top after being cut down is known as the cut-off elevation. For this project, the top-most thermal sensor was above the cut-off elevation or restated, the pile integrity can be assessed and converted to effective radius values up to the cut-off elevation. Figure 2.7 shows a pile group after excavation and pile cut-off.

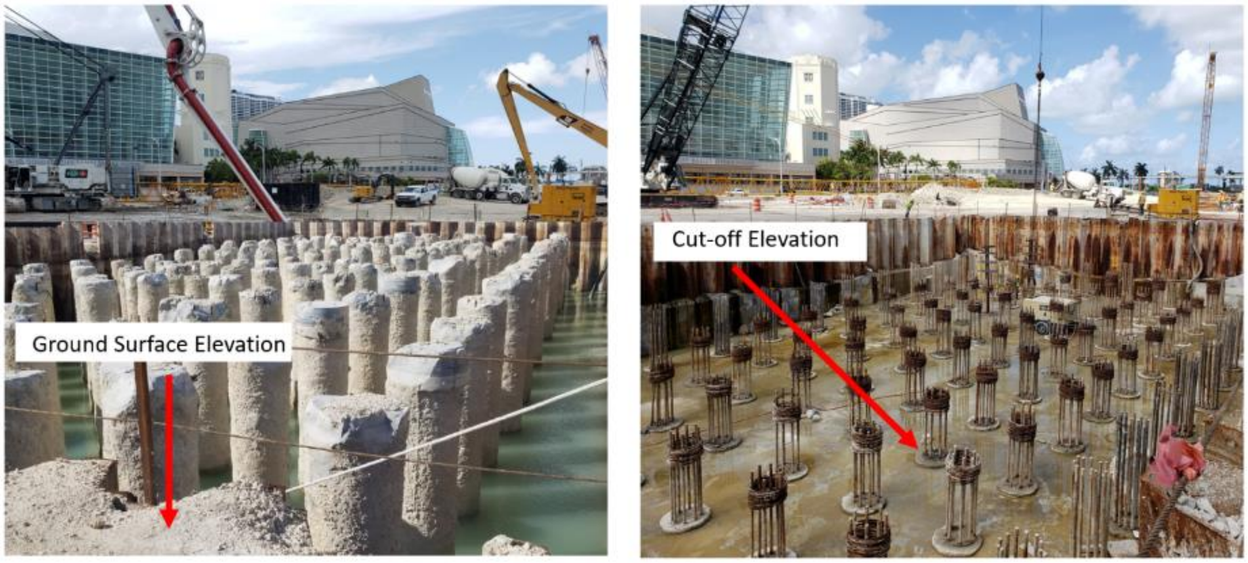


Figure 2.7 Fill excavated around a pile group for pile cap construction (left) and piles cut off exposing reinforcing steel (right)

Within the scope of this project and the data received thus far, as-built dimensions at cut-off have been recorded for some but not all piles. As-built dimensions include two diameter measurements (nearest the thermal wire locations N-S and E-W), a circumference measurement, and cover measurements (again adjacent to the thermal wire locations). Pile cover refers to the amount of grout between the outside of the vertical bar reinforcement and the outer cylindrical face of the pile. The cover region is especially important for corrosion resistance but can affect rebar bond/development length and bending resistance.

The two diameter measurements taken at the cut-off elevation are orientated in the north-south and east-west directions. This orientation is also used in the identification of the four thermal wires installed along the length of steel reinforcement. The circumference measurement is taken by wrapping a soft tape around the pile. The inspectors also take cover measurements at each of the four thermal wire locations (N-S-E-W). It is important to note that at the cutoff elevation, the stirrups of the reinforcement cage are not always visible, leading inspectors to reference the vertical rebar when recording cover measurements. To obtain the true cover measurement, the bar diameter of the stirrups is subtracted from the reported cover measurements. A complete diagram of the as-built dimensions at the cut-off elevation can be seen in Figure 2.8.

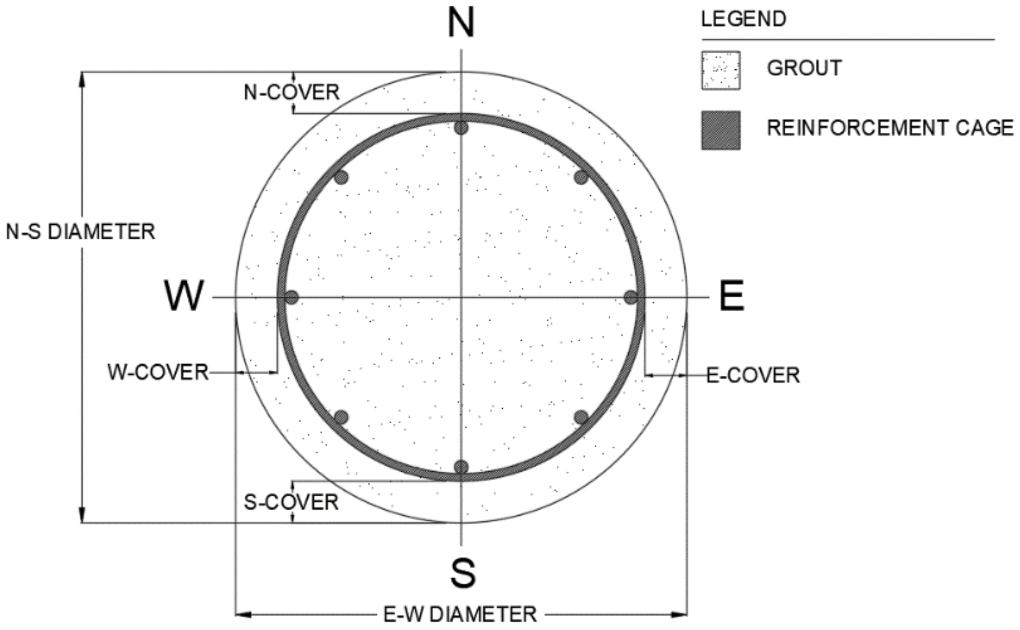
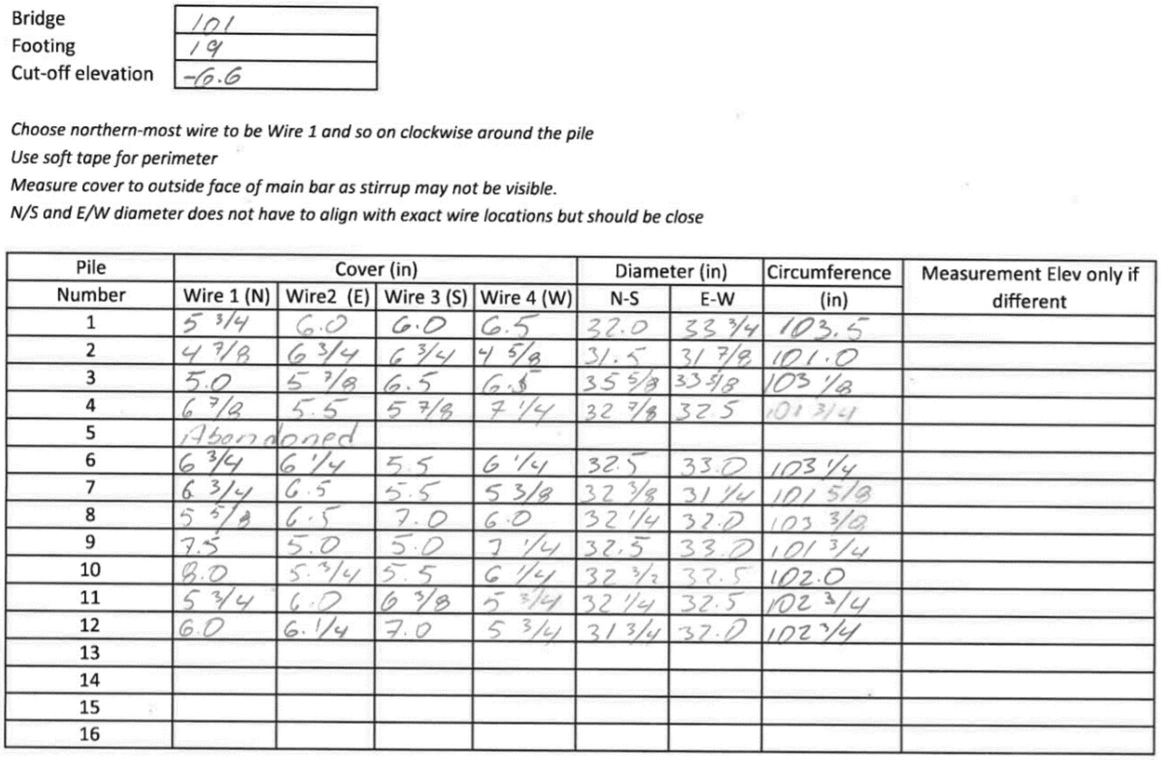


Figure 2.8 Diagram of all as-built measurements taken at pile cut-off elevation (Mee, 2022)

While these measurements are not available for every pile, a total of 366 piles of the data collected to date have as-built cut-off dimensions. An example field report for Bridge 101, Pier 19 with as-built dimensions can be seen in Figure 2.9.



Bridge	101
Footing	19
Cut-off elevation	-6.6

Choose northern-most wire to be Wire 1 and so on clockwise around the pile
Use soft tape for perimeter
Measure cover to outside face of main bar as stirrup may not be visible.
N/S and E/W diameter does not have to align with exact wire locations but should be close

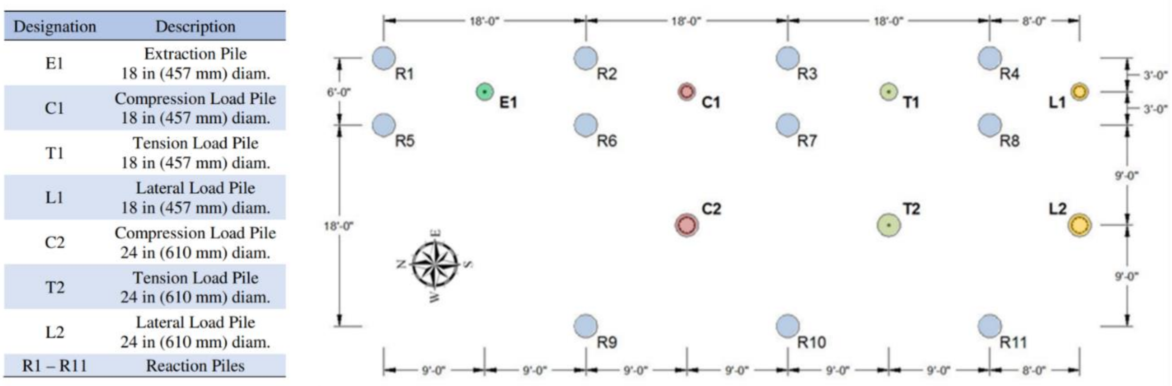
Pile	Cover (in)				Diameter (in)		Circumference	Measurement Elev only if different
Number	Wire 1 (N)	Wire2 (E)	Wire 3 (S)	Wire 4 (W)	N-S	E-W	(in)	
1	5 3/4	6.0	6.0	6.5	32.0	33 3/4	103.5	
2	4 7/8	6 3/4	6 3/4	4 5/8	31.5	31 7/8	101.0	
3	5.0	5 7/8	6.5	6.5	35 5/8	33 3/8	103 1/8	
4	6 7/8	5.5	5 7/8	7 1/4	32 7/8	32.5	101 3/4	
5	Abandoned							
6	6 3/4	6 1/4	5.5	6 1/4	32.5	33.0	103 1/4	
7	6 3/4	6.5	5.5	5 3/8	32 3/8	31 1/4	101 5/8	
8	5 5/8	6.5	7.0	6.0	32 1/4	32.0	103 3/8	
9	7.5	5.0	5.0	7 1/4	32.5	33.0	101 3/4	
10	8.0	5 3/4	5.5	6 1/4	32 1/2	32.5	102.0	
11	5 3/4	6.0	6 3/8	5 3/4	32 1/4	32.5	102 3/4	
12	6.0	6 1/4	7.0	5 3/4	31 3/4	32.0	102 3/4	
13								
14								
15								
16								

Figure 2.9 Bridge 101 – Pier 19 as-built dimensions at cut-off elevation

2.6 Deep Foundations Institute (DFI) Pilot Study

The first source of data came from a pilot study conducted by the DFI in coordination with the FDOT starting in 2016 and concluding in 2017. Auger cast piles had been widely used for private or commercial construction projects and non-bridge FDOT structures like sound walls. This study sought to perform a thorough analysis of the installation parameters and resulting pile performance to make recommendations on the use of auger cast piles for large publicly funded projects such as bridges. This study involved the detailed monitoring of auger cast pile installation with AME and post-installation TIP testing. The AME data was collected in the same manner as for production piles in the field.

After pile installation, load tests were performed to verify pile capacity. Two piles were loaded compressively, two were loaded laterally, and two were loaded in tension. The complete test pile layout and corresponding legend can be seen in Figure 2.10. The test piles denoted with the letter ‘R’ are reaction piles. These piles were used as support during load testing. For example, during the compressive load tests, large, stiffened I-beams spanned over the test pile and were tied into the reaction piles. Figure 2.11 shows the load test setup during a compressive load test.



Designation	Description
E1	Extraction Pile 18 in (457 mm) diam.
C1	Compression Load Pile 18 in (457 mm) diam.
T1	Tension Load Pile 18 in (457 mm) diam.
L1	Lateral Load Pile 18 in (457 mm) diam.
C2	Compression Load Pile 24 in (610 mm) diam.
T2	Tension Load Pile 24 in (610 mm) diam.
L2	Lateral Load Pile 24 in (610 mm) diam.
R1 – R11	Reaction Piles

Figure 2.10 DFI pilot study test pile locations and legend (Marinucci & NeSmith., 2017)

Figure 2.11 DFI pilot study compressive load test setup (Marinucci & NeSmith., 2017)

Furthermore, one test pile was designated for extraction to evaluate the physical as-built dimensions for comparison to the dimensions predicted by TIP data and monitored grout volume.

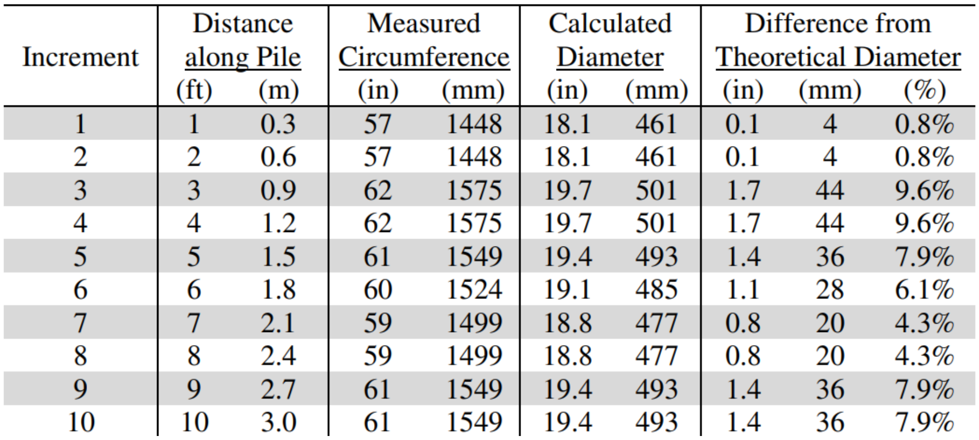
2.7 Test Pile Extraction

To extract the pile, 14-inch diameter relief holes were drilled around the pile to reduce the uplift capacity of the pile and facilitate extraction. Four reaction piles and the load test frame were configured for a pile tension test, as seen in Figure 2.12.

Figure 2.12 Tension load test setup used to extract auger cast pile E-1 (Marinucci & NeSmith., 2017)

Once extracted 2 to 3ft using the tension load testing setup, a crawler-crane was used to extract the pile completely out of the ground, as seen in Figure 2.13. After extraction, the pile was pressure washed to remove any dirt and debris, allowing for accurate measurements of the as-placed grout and pile size. The pile was placed horizontally on supports and circumference measurements were taken at 1ft intervals (Figure 2.13) along the length of the pile. While the total pile length for pile E-1 was 40ft, Figure 2.14 provides the first 10 circumference measurements.

Figure 2.13 Pile completely extracted using crawler-crane (left) circumference measurements taken at 1-foot intervals along pile length (right) (Marinucci & NeSmith., 2017)



Increment	Distance along Pile		Measured Circumference		Calculated Diameter		Difference from Theoretical Diameter		
	(ft)	(m)	(in)	(mm)	(in)	(mm)	(in)	(mm)	(%)
1	1	0.3	57	1448	18.1	461	0.1	4	0.8%
2	2	0.6	57	1448	18.1	461	0.1	4	0.8%
3	3	0.9	62	1575	19.7	501	1.7	44	9.6%
4	4	1.2	62	1575	19.7	501	1.7	44	9.6%
5	5	1.5	61	1549	19.4	493	1.4	36	7.9%
6	6	1.8	60	1524	19.1	485	1.1	28	6.1%
7	7	2.1	59	1499	18.8	477	0.8	20	4.3%
8	8	2.4	59	1499	18.8	477	0.8	20	4.3%
9	9	2.7	61	1549	19.4	493	1.4	36	7.9%
10	10	3.0	61	1549	19.4	493	1.4	36	7.9%

Figure 2.14 First 10 pile measurements of pile E-1 as part of the DFI pilot study (Marinucci & NeSmith., 2017)

The measured pile radius was obtained from two circumference measurements and one caliper measurement at each 1-foot interval of pile length. Pile size was predicted using incremental volume recorded using both pump strokes and the in-line magnetic flow meter. Figure 2.15 shows the measured and predicted pile size as a function of depth for pile E-1.

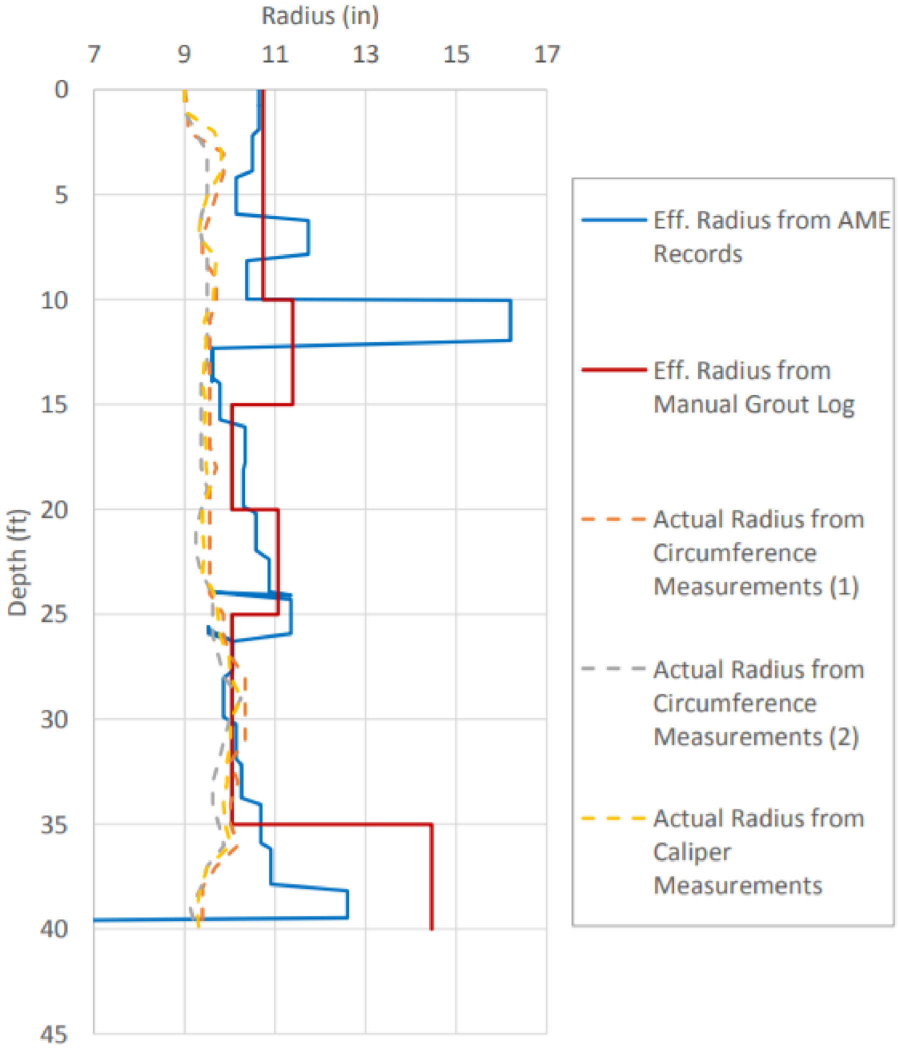


Figure 2.15 Pile E-1 measured and predicted dimensions (Mullins & Johnson, 2017)

Effective radius from AME records refers to the radius as calculated using the volume recorded by the in-line magnetic flow meter. The effective radius is calculated at each 2ft interval along the length of the pile using the following equation:

$$R_{AME} = \sqrt{\frac{V_{AME}}{\pi L_{incremental}}} \tag{2.1}$$

where: V_{AME} = *AME recorded volume over 2ft of pile length*
$L_{incremental}$ = *2ft*

Similarly, effective radius from the manual grout log refers to the radius as calculated using volume from counting pump strokes (audibly or by feel) during grouting following the equation:

$$R_{pump-strokes} = \sqrt{\frac{V_{pump-strokes}}{\pi L_{incremental}}} \quad (2.2)$$

where: $V_{pump-strokes}$ = *pump stroke volume recorded over 5ft of pile length*
$L_{incremental}$ = *5ft*

The grout volume from pump strokes is calculated using the following equation:

$$V_{pump-strokes} = N_{ps}(C_{ps}) \quad (2.3)$$

where: N_{ps} = *number of pump strokes over 5ft of pile length*
C_{ps} = *grout pump calibration coefficient (cuft/stroke)*

As expected, the caliper measurement and two circumference measurements are in close agreement along the length of the pile. However, pile radius calculated from both volume monitoring methods over-predict as-built pile size. Furthermore, the grout volume measured with the magnetic flow meter yielded a different pile radius than the grout volume obtained from counting pump strokes. While a grout volume analysis is beyond the scope of the Task 1 report, the uncertainty surrounding grout volume accounting is a major motivation for this study.

2.8 I-395 Expansion Project

Formally known as the I-395/SR 836/I-95 Design-Build Project, this infrastructure project will improve the mobility of residents, commuters, and tourists by increasing the capacity of I-395, SR 836, and I-95 at their intersection in Miami, Florida (FDOT & MDX, 2021). This project represents a partnership between the Florida Department of Transportation and the Miami-Dade Expressway Authority (MDX). The project consists of three major objectives that include: (1) constructing a double deck for SR 836, (2) concrete pavement replacement, lane addition, and a new connector ramp for I-95, and (3) I-395 facility improvements and construction of a signature bridge.

The I-395 signature bridge will be 1,025ft long and span over NE 2nd Ave. and Biscayne Boulevard. There will be six arches that start from the center pier and cross outward to support the bridge deck with cables, as seen in Figure 2.16. While the bridge superstructure is visually striking, the foundation elements will be the focus of this study. Seven foundations support the signature bridge, six below each arch and one below the center pier, where each arch spans outward. The majority of auger cast piles being installed are 2.5ft in diameter with a 21in diameter reinforcement cage ranging from depths of 70 to 120ft below the existing ground surface. The auger cast piles under the center pier of bridge 8 are 3ft in diameter with 27in cages and extend approximately 120ft below existing grade. Figure 2.17 shows all 128 piles under the center pier completed before construction of the center pier footing.

Figure 2.16 I-395 signature bridge rendering (FDOT & MDX, 2021)

Figure 2.17 I-395 signature bridge center pier construction

2.9 Overview of Previously Collected Data

During pile installation, FDOT inspectors collected key pieces of installation data to verify pile integrity post-construction. To date, researchers at the University of South Florida have received installation data from a total of 1050 piles, representing 80 piers and 9 bridges. The installation data received for each pile consisted of:

1. Thermal Integrity Profiling (TIP) data and associated report
2. Automated Measuring Equipment (AME) data
3. Installation logs
4. Drop hammer load test results
5. As-built pile dimensions recorded at the cut-off elevation

Drop hammer tests were only being performed on roughly 5% of the production piles and are not critical in the evaluation of as-placed grout volume. Although load testing data was received, it was excluded from the summary of previously collected data. Table 2.1 provides the quantity of each data type received and catalogued.

Table 2.1 Data Type Quantity Summary

Data Type	Quantity
TIP Data/Report	890
AME Data	883
Installation Logs	897
As-Built Dimensions	366

Thermal Integrity Profiling (TIP) data has been received in both the raw form and in a TIP report. The TIP report provides critical information on the general temperature profile of the pile and the temperature at the cut-off elevation. Parameters from the TIP report will be used in the future analysis of as-placed grout volume. If adjustments to the thermal analysis are required, the raw data can be opened in the analysis software provided by Pile Dynamics, Inc. (PDI). For initial cataloging purposes, the raw TIP data and the TIP reports were bundled together.

The AME data comes as an excel sheet with all of the drilling and grouting parameters described in section 2.2 as a function of time. The AME data provides a holistic view of all parameters during both the drilling and grouting operations. The presence of TIP data/reports, AME data, and installation logs are most common in a pile with a complete data set. As-built dimensions have only been catalogued for 366 piles. Figure 2.18 provides a graphical representation of all catalogued data to date.

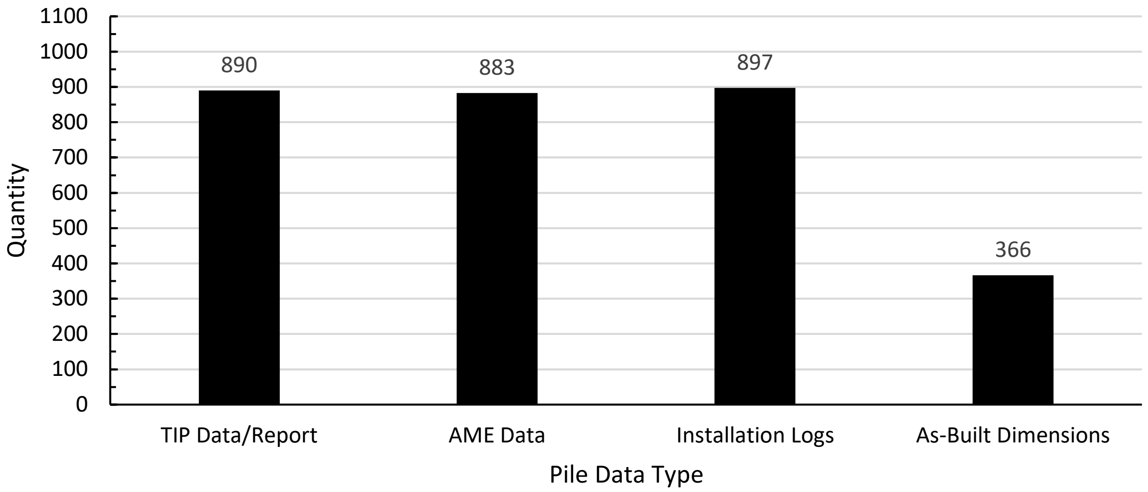


Figure 2.18 Summary of data types and associated quantities from the I-395 Expansion Project

A folder was created for each auger cast pile containing all installation data (TIP data/reports, AME data, installation logs, etc.) that was received. The pile folders were organized by pier and by bridge for ease of retrieval. Tables were constructed for each pier showing the data that has been catalogued for each pile within that respective pier. The pier tables were organized by bridge number and included in the Appendices. Table 2.2 outlines the location within the appendices.

Table 2.2 Location of cataloged data summaries for each bridge

Bridge	Corresponding Appendix
Bridge 4	Appendix A
Bridge 5	Appendix B
Bridge 7	Appendix C
Bridge 8	Appendix D
Bridge 11	Appendix E
Bridge 101	Appendix F
Bridge 102	Appendix G
Bridge 103	Appendix H
Bridge 104	Appendix I

2.10 Summary of Preliminary Analysis

The AME records provide the depth of the auger tip as a function of time during the drilling and grouting operations. During auger cast pile installation, the soil-filled auger flights are responsible for proving excavation stability. Removal of the auger before completion of the grouting operation leaves the hole unsupported. It is of interest to investigate piles that experienced auger removal during the drilling or grouting operation. Mechanical issues with the drill rig or grouting issues are typical causes of auger removal before fully grouting the pile. The term re-stroking has been introduced to describe the removal and re-insertion of the auger in a fashion not typical to pile installation.

During drilling, a partial re-stroke is defined as the lifting of the auger above the current drilling depth without completely exiting the excavation. A complete re-stroke during drilling involves removing the auger completely from the excavation and re-inserting the auger to resume drilling. During grouting, a partial re-stroke is defined as the sudden lifting of the auger above the current grouting depth without pumping grout. A complete re-stroke during grouting involves the full removal of the auger from the excavation, leaving the remainder of the pile un-grouted. This may occur due to blockage in the grouting system or failure to blow the grout plug from the bottom of the hollow stem auger. Determining if a partial or complete re-stroke has occurred during pile installation requires AME data.

Another area of interest is the level of agreement between the grout volume as measured by the in-line magnetic flow meter and as calculated from the number of pump strokes and the grout pump calibration. The AME data contains the grout volume measured from the flow meter and the installation log contains the number of pump strokes for each 5ft increment of grouted pile length. Both grout volumes can be plotted against each other to evaluate their level of agreement. This analysis requires that a pile has complete AME records and installation logs.

As previously described, the AFF is an essential parameter for calculating the total pile volume and acceptance. The pile volume is also used to develop the T-R relationship for TIP analysis. Currently, an AFF of 0.6 is being used during pile volume calculations but values as high as 0.85 have been reported. To develop a statistical range of AFF values, as-built measurements at the cut-off elevation were used. Briefly, knowing the actual dimension of the pile at the cut-off elevation enables the back-calculation of the AFF required to match the TIP predicted cut-off dimensions to those measured. This analysis is performed to determine an accurate AFF for use in future pile volume reporting.

Chapter Three: Data Presentation and Newly Collected Data

Chapter 3 introduces initial data visualizations to aid in evaluating auger cast installation and grout volume monitoring practices. The following visualizations are available for every auger cast pile currently catalogued. It is envisioned that a dynamic database containing all auger cast piles will be made available upon submittal of the final report. This database would allow users to select any given pile and plot any number of installation parameters. After presenting these initial plots, Chapter 3 will provide a comprehensive summary of data collected after the submittal of the Task 1 deliverable. Note analysis is not the focus of this chapter, but rather the primary goal was the collection and cataloguing of the information from 5356 documents for 1179 piles at present.

The data sources presented include AME records, installation logs, and field measurements of the as-built piles.

3.1 Automated Measuring Equipment (AME) Logs

Each auger cast pile catalogued includes a detailed accounting of construction parameters recorded by Automated Measuring Equipment (AME). See section 2.2 for a complete list of transducers that are recording data during pile installation. For each auger cast pile, plots were created to better visualize the relationship between each variable and auger tip depth or elapsed time. The auger tip depth, crowd pressure, and gear box hydraulic pressure are shown as a function of time in Figures 3.1, 3.2, and 3.3, respectively.

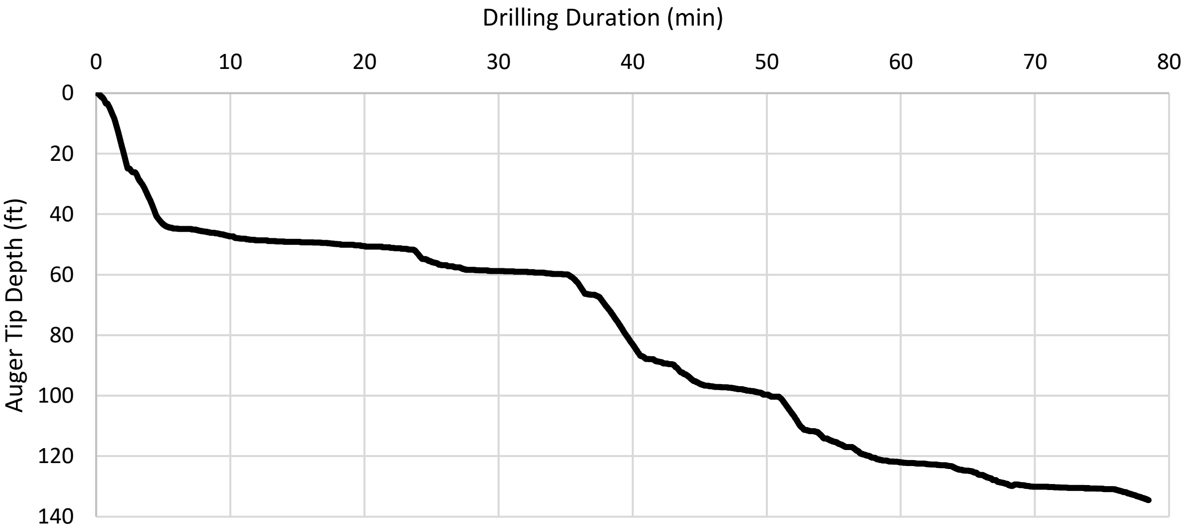


Figure 3.1 Auger tip depth over duration of drilling (data from Bridge 8 – Center Pier – Pile 1)

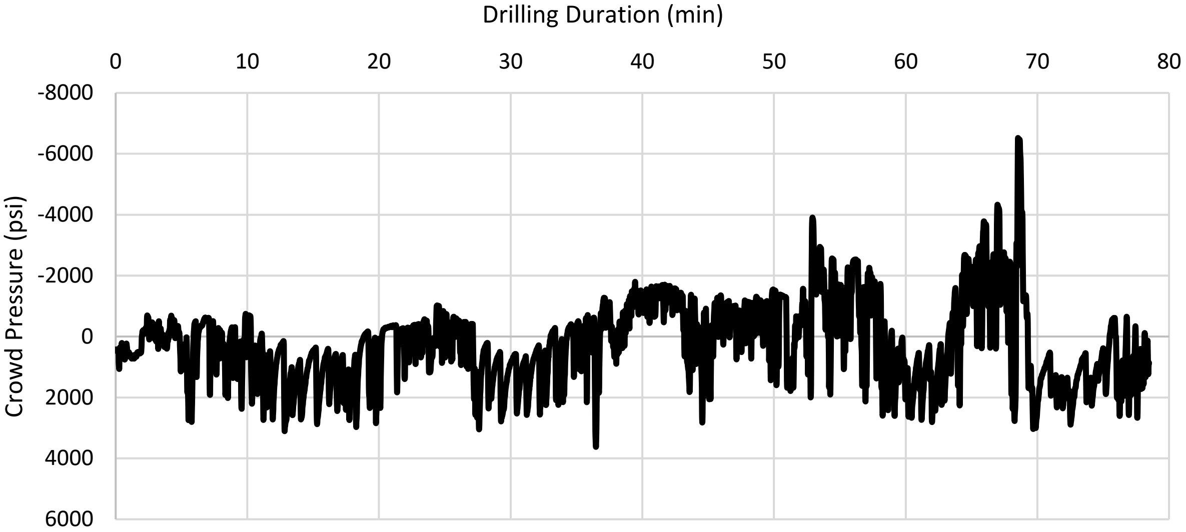


Figure 3.2 Crowd pressure during drilling (data from Bridge 8 – Center Pier – Pile 1)

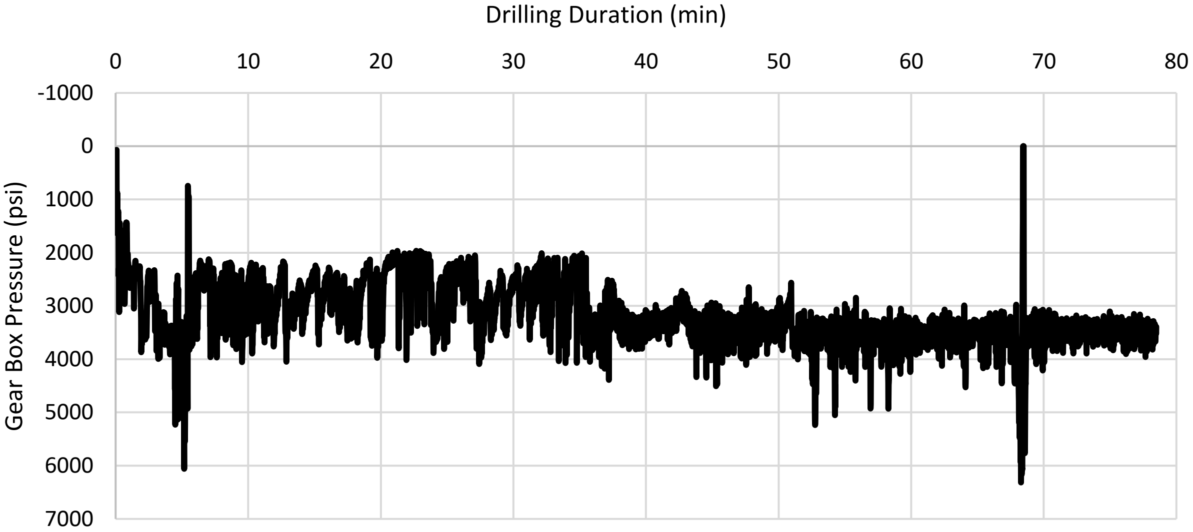


Figure 3.3 Gear box pressure over duration of drilling (data from Bridge 8 – Center Pier – Pile 1)

Figures 3.4 and 3.5 show the auger tip depth and accrued flow meter grout volume as a function of grouting duration, respectively. Figure 3.6 shows the placed grout volume with respect to auger tip depth.

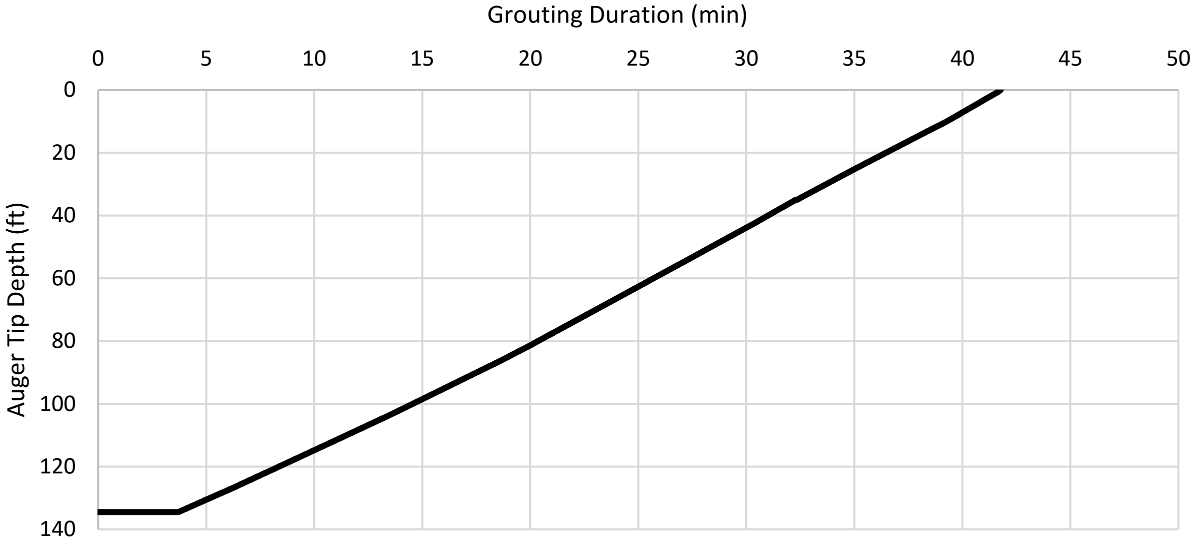


Figure 3.4 Auger tip depth over duration of grouting (data from Bridge 8 – Center Pier – Pile 1)

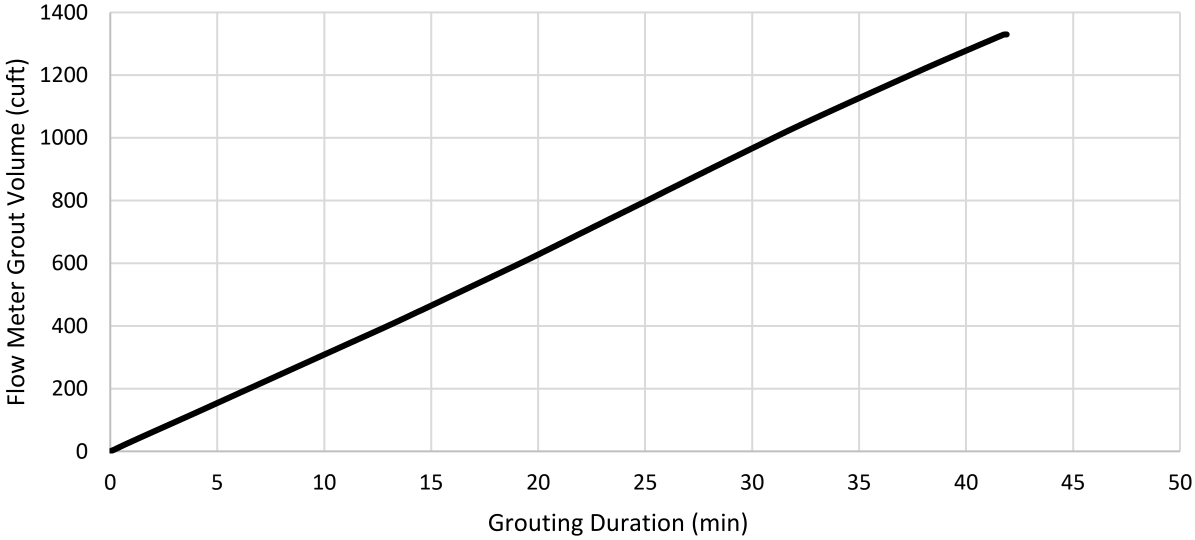


Figure 3.5 Flow meter grout volume over duration of grouting (data from Bridge 8 – Center Pier – Pile 1)

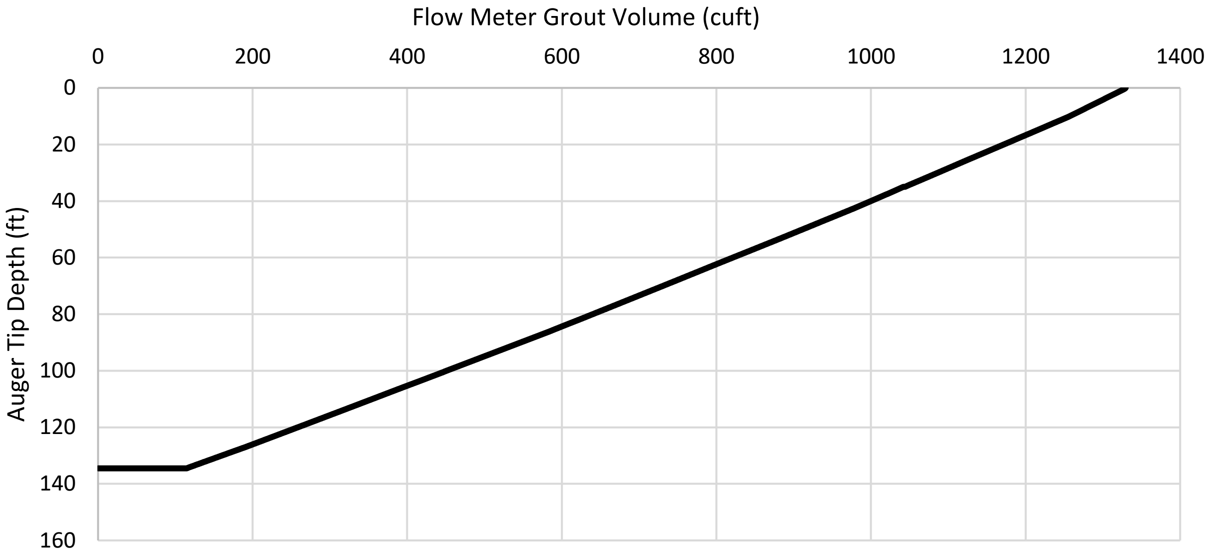


Figure 3.6 Flow meter grout volume as a function of auger tip depth (data from Bridge 8 – Center Pier – Pile 1)

While inspectors record the number of pump strokes for every 5ft length of pile grouted in the installation logs, pump strokes are also recorded by AME. Figure 3.7 shows AME recorded pump strokes throughout the grouting operation. The grout pressure developed by the positive displacement pump is recorded, shown in Figure 3.8, and is an important parameter in successful pile construction. Figure 3.9 shows the same pressure profile at a closer scale, where the individual pump strokes can be identified.

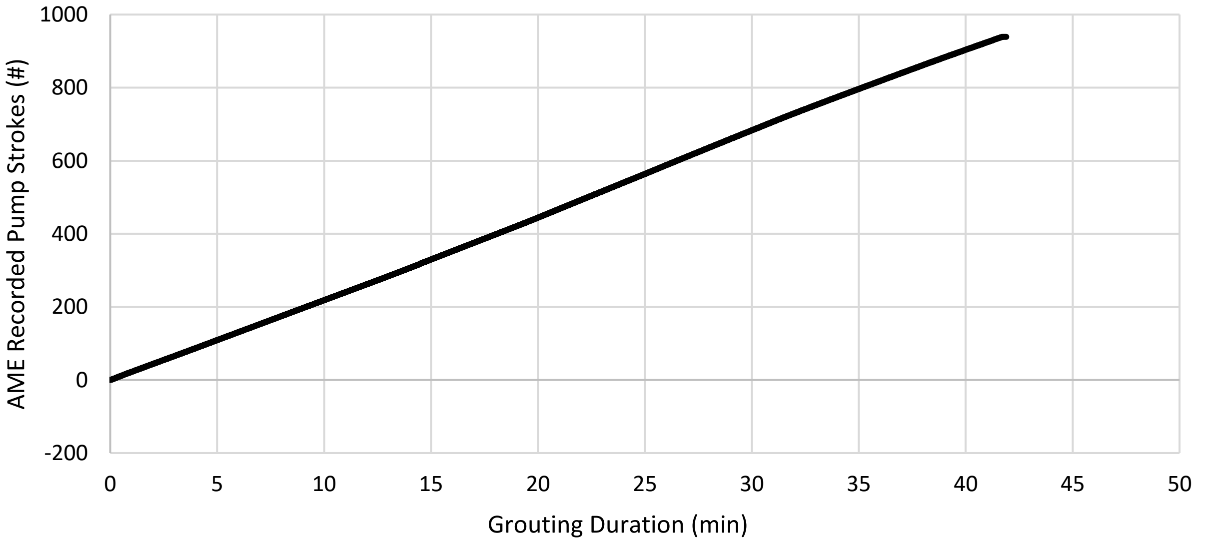


Figure 3.7 AME recorded pump strokes over duration of grouting (data from Bridge 8 – Center Pier – Pile 1)

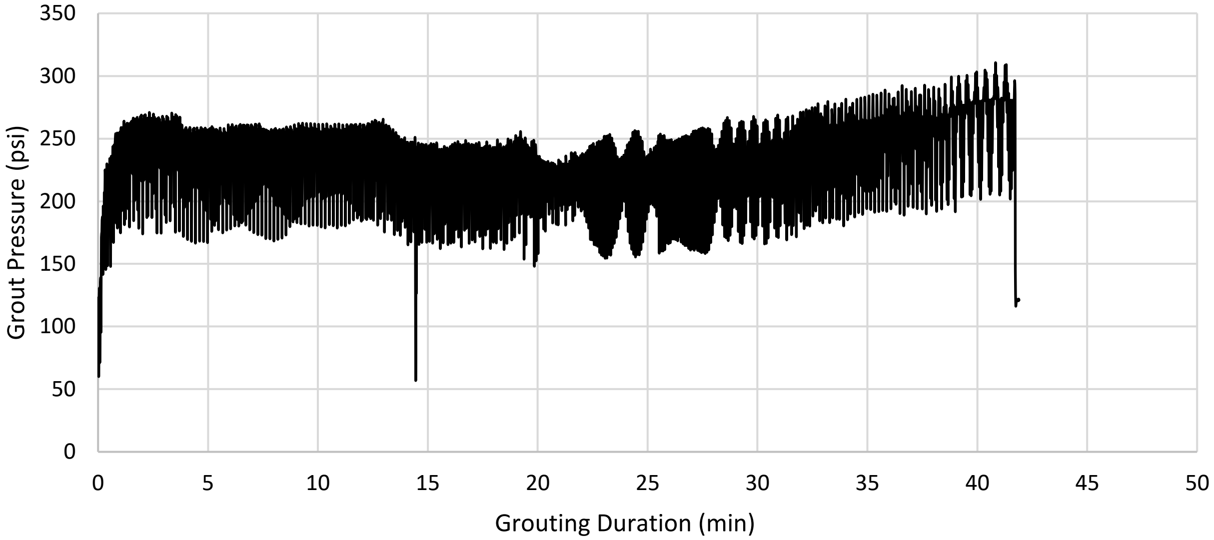


Figure 3.8 Grout pressure over duration of grouting (data from Bridge 8 – Center Pier – Pile 1)

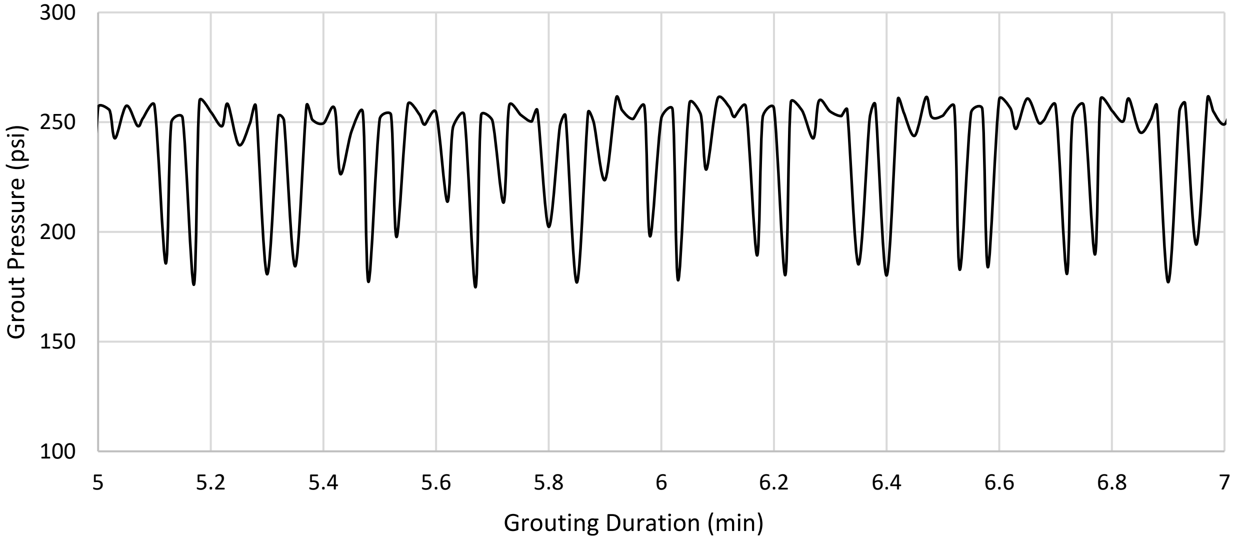


Figure 3.9 Exploded view of grout pressure between 5 and 7 minutes of grouting (data from Bridge 8 – Center Pier – Pile 1)

3.2 Installation Logs

Data recorded by field inspectors culminates in an installation log which enables verification of successful pile installation and a backup in case of AME malfunction or data loss. Figure 3.10 shows the number of pump strokes recorded for each 5ft increment of auger extraction. Cumulative pump strokes over the whole grouting operation are seen in Figure 3.11. Corresponding grout volume is calculated by multiplying the number of pump strokes by the pump calibration (cuft/stroke), as seen in Figure 3.12.

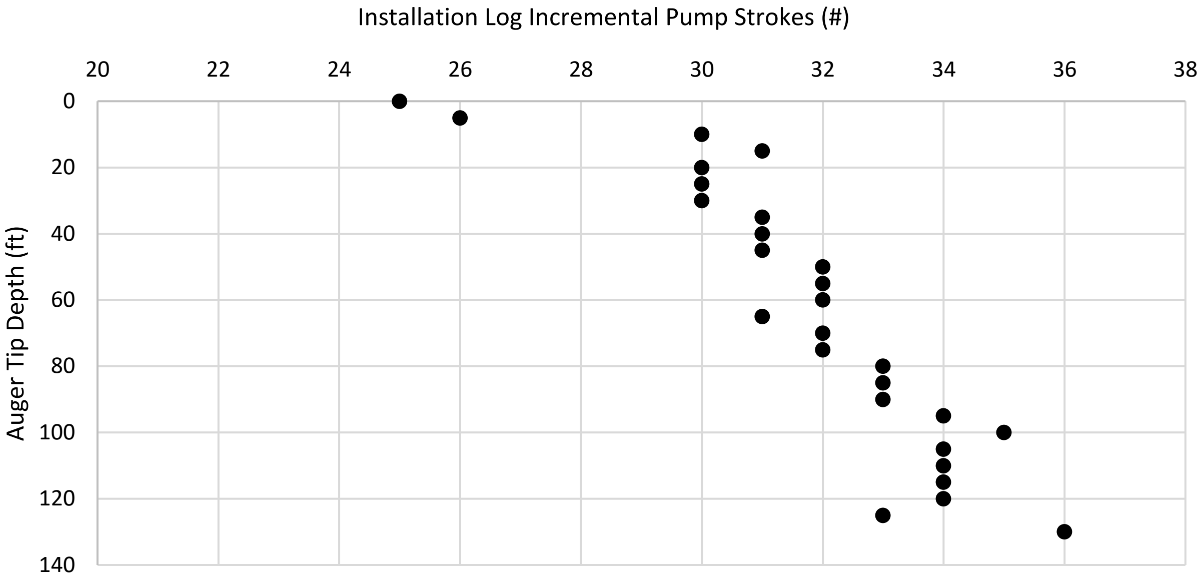


Figure 3.10 Incremental pump stroke count at every 5ft of auger extraction(data from Bridge 8 – Center Pier – Pile 1)

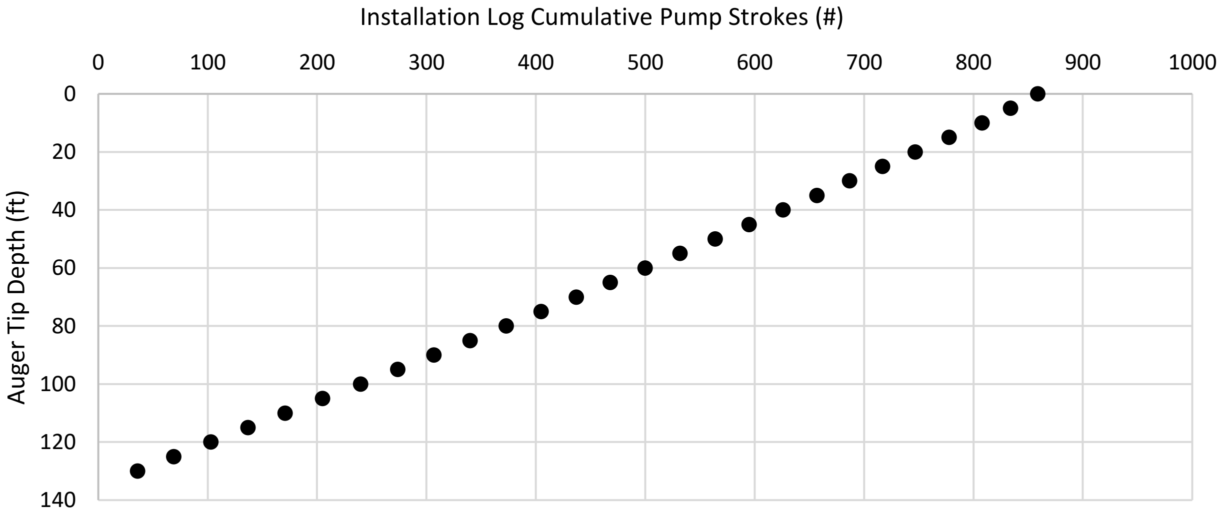


Figure 3.11 Cumulative pump strokes over entire grouting operation (data from Bridge 8 – Center Pier – Pile 1)

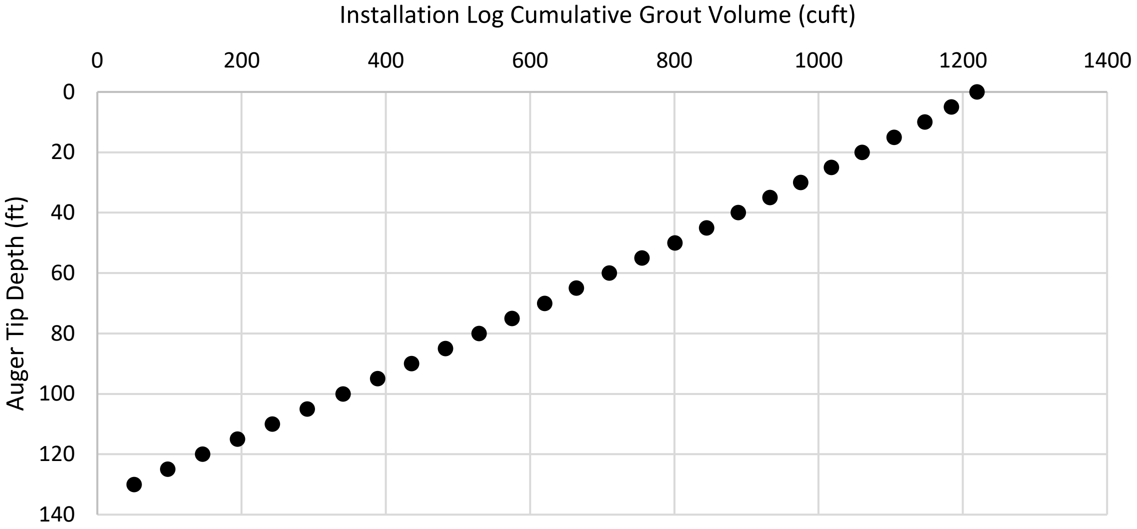


Figure 3.12 Cumulative grout volume versus auger tip depth (data from Bridge 8 – Center Pier – Pile 1)

3.3 Field Measurements

As discussed in section 2.5, field measurements taken at the cut-off elevation are available for selected piers. To date, field measurements for 184 ACIP piles have been catalogued. While not simply a data collection effort, this data is best shown with an initial comparison between measured and predicted pile diameter. Pile diameter at the as-reported cut-off elevation was predicted using the pile grout volume (again as-reported), the calculated T-R constant, and the average measured temperature at the cut-off elevation. It should be noted that pile grout volume was calculated using an AFF value of 0.6 for all piles presented. Figure 3.13 shows predicted vs. measured pile diameter for all 184 piles, with the black dashed line representing a one-to-one perfect agreement between the two.

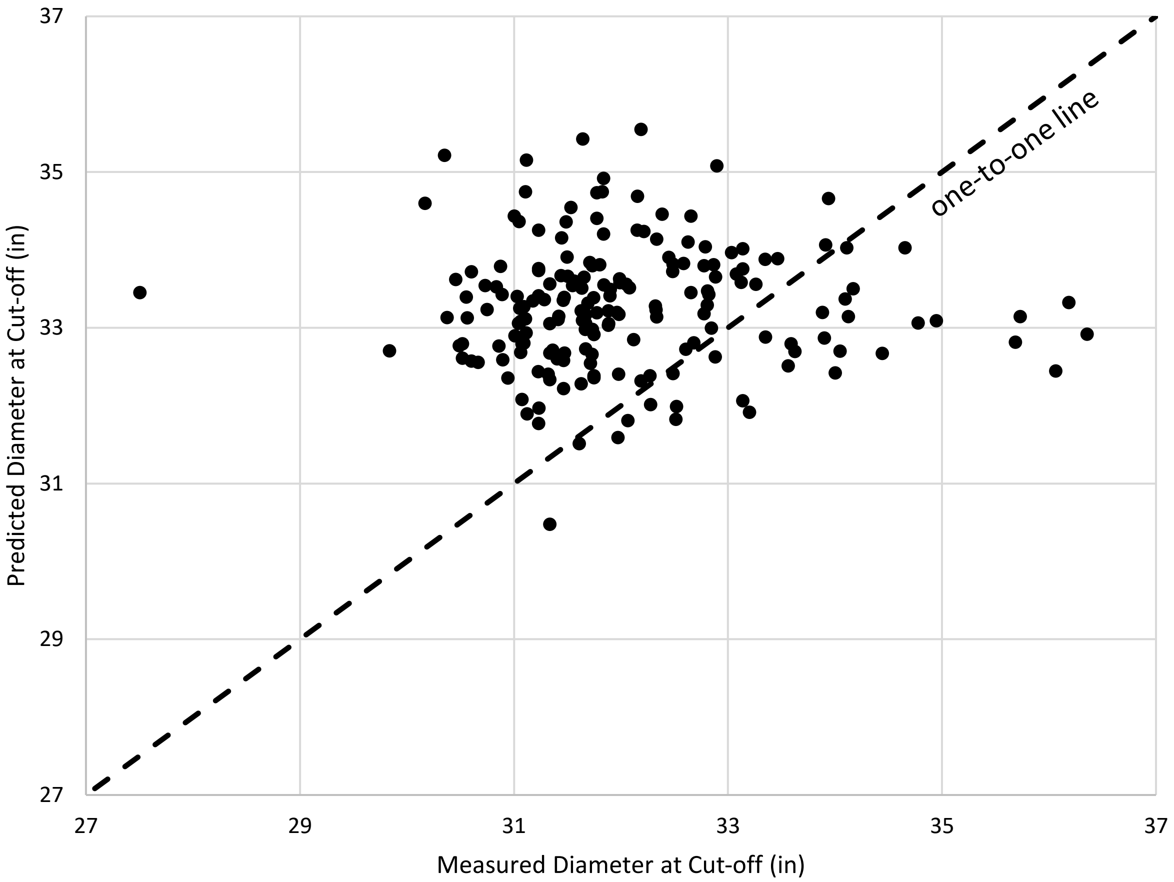


Figure 3.13 Predicted vs. measured diameter at cut-off elevation for 184 piles

From Figure 3.13, bias values are calculated for all piles. The bias is defined as the measured pile diameter divided by the predicted pile diameter. A bias greater than 1 represents an underprediction of pile diameter and a bias less than 1 represents an overprediction. Figure 3.14 shows the bias distribution for 184 piles, largely following a normal distribution. It should be noted that a majority of piles showed an overprediction of pile size at cut-off using current evaluation methods. Figure 3.15 further expresses this trend of overprediction in terms of percent error between measured and predicted values.

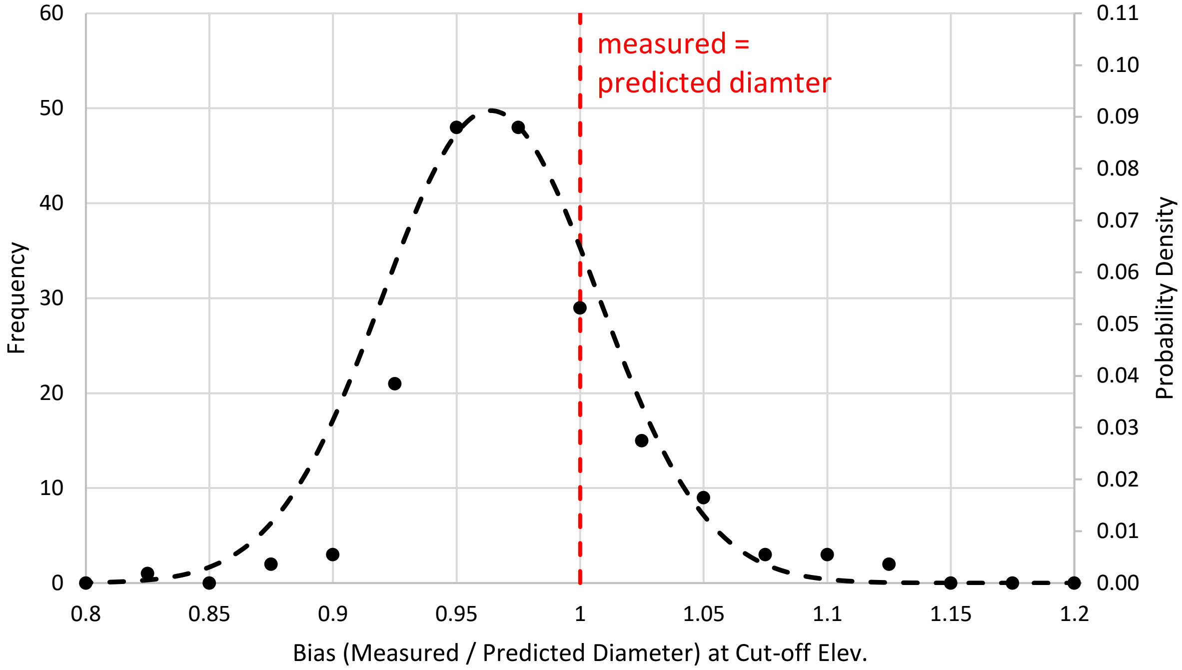


Figure 3.14 Bias distribution and superimposed normal distribution for 184 piles

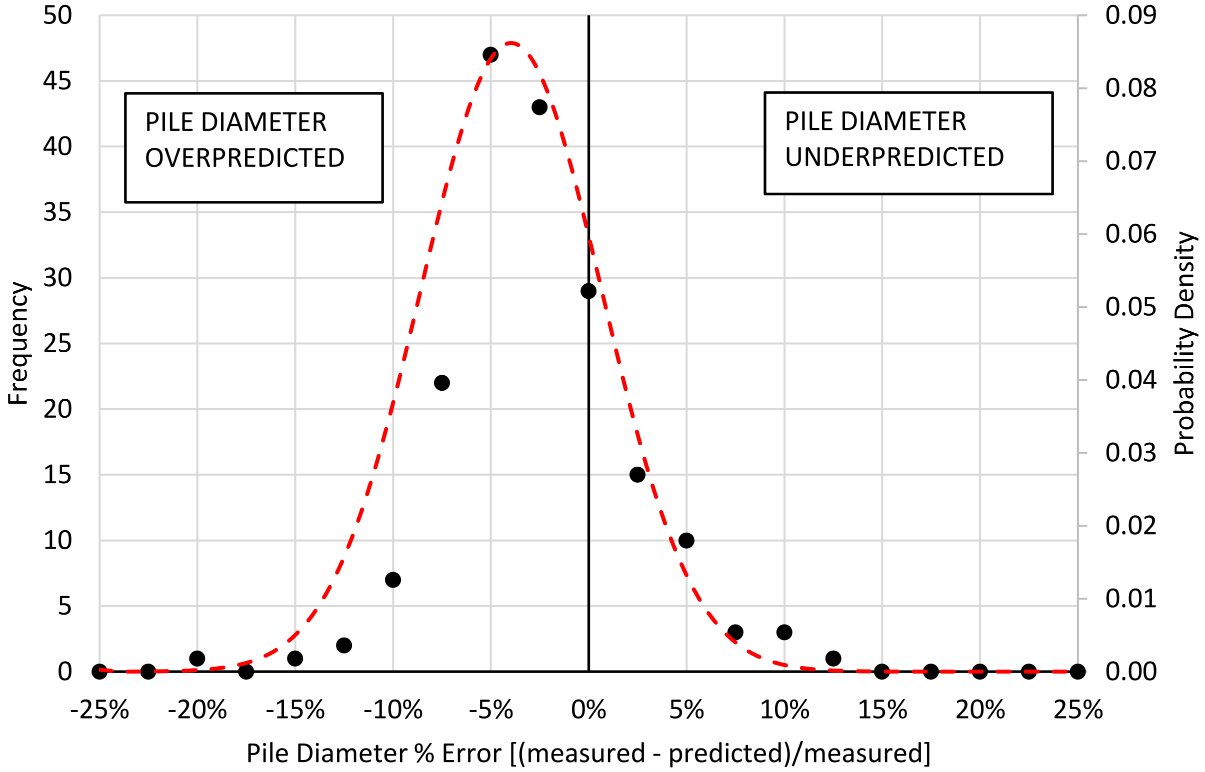


Figure 3.15 Percent error in pile diameter predictions for 184 piles

3.4 Auger Re-stroking

During auger cast pile construction, drilling should be continuous to maintain a full auger and excavation stability. The auger should not be removed or lifted above the current auger tip depth during drilling. While grouting, the grout replaces the soil-filled auger as the stabilizing element in the excavation. Deviation from controlled extraction would leave sections unsupported. Brown et al. (2007) notes that an unsupported excavation can cause cave-ins, loss of soil structural integrity, and other anomalies.

Where Figures 3.1 and 3.4 represent recommended construction practice per Brown et al. (2007), deviations from this practice make total grout volume determine difficult and can lead to the concerning conditions noted above. The auger tip depth as a function of drilling/grouting time were plotted to identify instances of auger removal that did not meet recommended practices. To differentiate between types of auger extraction, two terms are defined as follows:

Partial re-stroke: the auger tip is extracted above the current drilling/grouting point and reinserted to continue the current operation.

Complete re-stroke: the auger tip is extracted to the ground surface, completely exiting the pile excavation, then reinserted to resume the current operation.

Partial or complete re-strokes during grouting may or may not be an issue depending on if the excavation is left open and unsupported by the grout.

Auger re-stroking, if present, can be identified on a plot of auger tip depth versus time, as previously shown in Figure 3.1. Figure 3.16 (a combination of Figures 3.1 and 3.4) shows auger tip depth during both drilling and grouting, where no re-strokes are present.

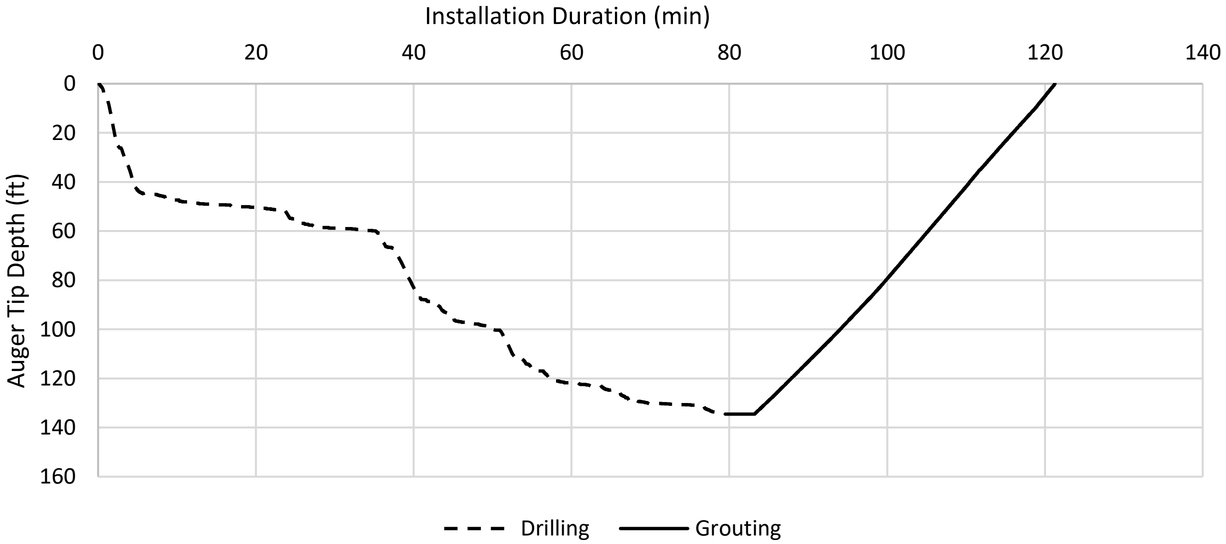


Figure 3.16 Auger cast pile construction with no re-stroking (data from Bridge 8 – Center Pier – Pile 1)

Figure 3.17 shows an instance where the auger was both partially and completely removed while drilling. Figure 3.18 shows a similar occurrence of re-stroking during grouting. To clearly identify that re-stroking during grouting occurred, Figure 3.19 shows that no grout was pumped during these instances of auger extraction.

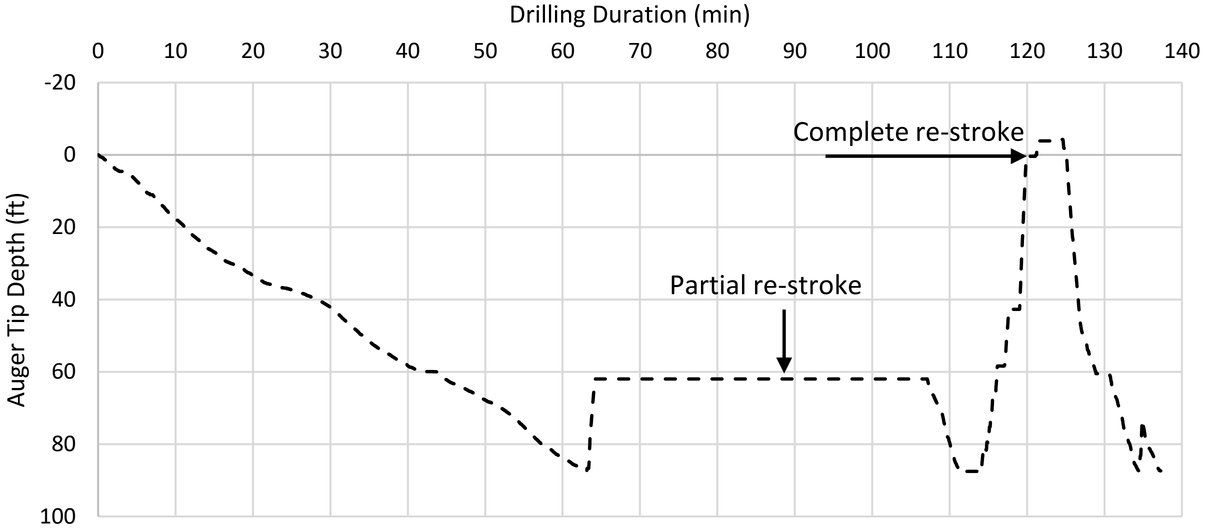


Figure 3.17 Example of one partial and one complete re-stroke during drilling (data from Bridge 4 – Pier 4L – Pile 1)

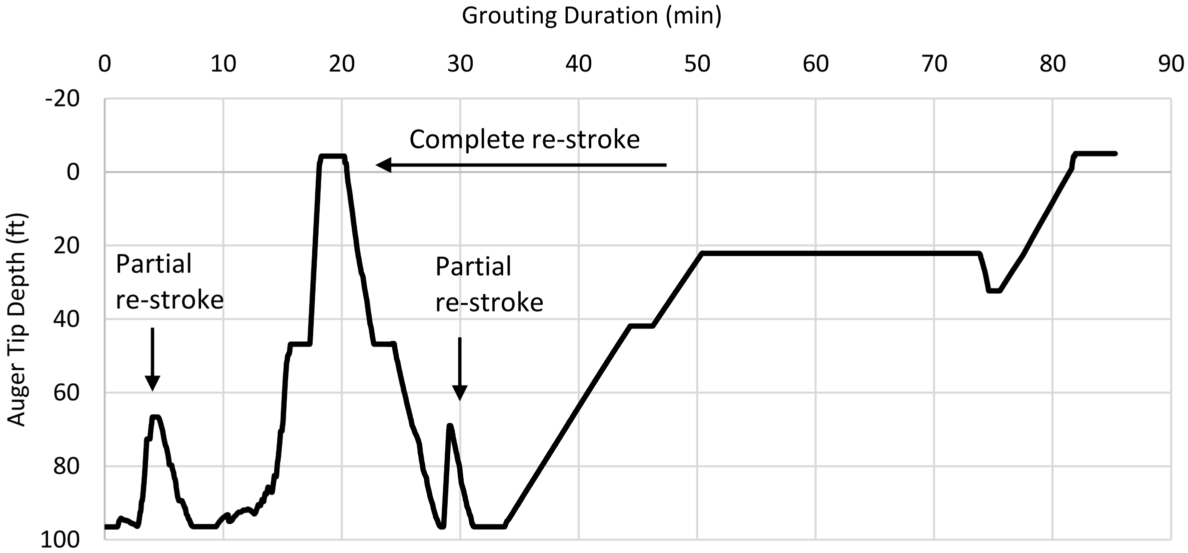


Figure 3.18 Example of two partial re-strokes and one complete re-stroke during grouting (data from Bridge 7 – Pier 9L – Pile 5)

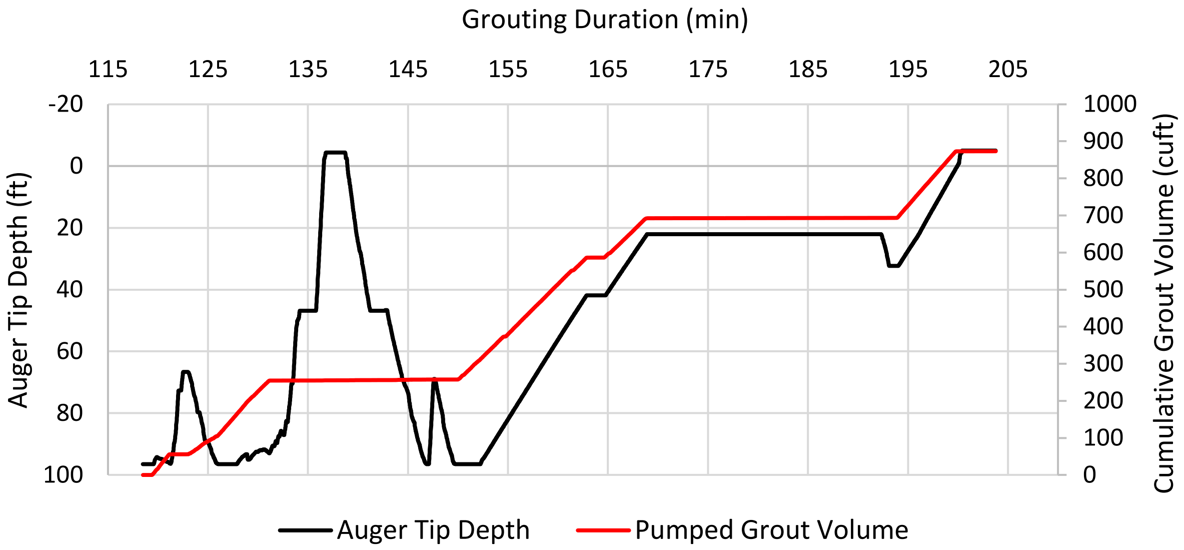


Figure 3.19 Pumped grout volume overlay showing no pumped grout during complete re-stroke and second partial re-stoke (data from Bridge 7 – Pier 9L – Pile 5)

Chapter Four: Data Analysis

Chapter four presents the data analysis conducted on the 1179 auger cast piles compiled / within the database followed by findings and recommendations for better construction practices presented. Chapter four is divided into categories based on the type of analysis performed as follows:

1. Evaluation of 386 auger cast piles for re-stroking frequency during drilling and grouting.

2. Comparison of grout volume tracked by counting pump strokes and by in-line magnetic flow meters for 651 auger cast piles. A subset of 51 piles contained truck volumes and corresponding pump strokes per truck. The three independent volume records (pump strokes, flow meter measurements, and truck volume) were further compared.

3. For a subset of 48 piles where as-built dimensions at the cut-off were recorded, reported pile diameters (with an assumed AFF of 0.85) vs measured pile diameters were presented. As-built dimensions were used to back-calculate a statistical range of AFF values, and a more appropriate means of selection is explored.

4. The effect of near-surface soil temperature variation is explored and its potential to affect pile size predictions at the location of as-built measurements.

5. Two modes of soil adhesion to the auger are presented and a preliminary survey of common auger sizes is conducted to provide a range of empty auger AFF values. Sample inspector guides are proposed to aid in visual estimation of AFF.

It should be noted that the quantity of piles used in conducting each analysis type depended on the availability and completeness of pile installation data. For example, the absence of AME data limited the ability to plot auger tip depth vs. time and identify re-stroking events.

4.1 Evaluation of Auger Re-stroking Events

Section 3.4 defined auger re-stroking and the potential implications of re-stroking on excavation stability. Table 4.1 presents the analysis of AME data from 386 auger cast piles where re-stroking was observed to be a common occurrence. It should be noted that many piles were observed to have multiple re-stroking events (e.g., one partial re-stroke during drilling and one complete re-stroking during grouting), hence a larger number of recorded re-strokes than total piles analyzed.

Table 4.1 Summary of observed re-strokes

Piles with at least one...	# of Piles	%	of	Total Piles Analyzed
Partial Re-stroke during Drilling	203	52.6%	of	386
Complete Re-stroke during Drilling	114	29.5%	of	386
Partial Re-stroke during Grouting	63	16.3%	of	386
Complete Re-stroke during Grouting	25	6.5%	of	386

Re-stroking data is specific to the site conditions and contractor and is not presented as a commentary on pile contractors, but rather as a means of illustrating the difficulty of installing auger cast piles in a continuous manner as intended. Extraction of the auger during grouting introduces additional complexity when estimating final pile volume and the possibility of soil relaxation. Furthermore, unlike drilled shafts that utilize mechanical casing or support fluid to maintain excavation stability, auger cast piles rely on a fully soil-laden auger.

4.2 Comparison of Flow Meter and Pump Stroke Volume

While grouting auger cast piles, placed grout volume is tracked by counting pump strokes and through use of an in-line magnetic flow meter monitored by AME onboard the drill rig. Pump stroke counting requires an accurate calibration constant (volume/stroke) determined for FDOT following test designation FM 5-612. Grout pump calibration is required before installation of demonstration piles, before construction of every two piers/bents, or at the engineer's discretion (FDOT, 2023). Table 4.2 shows an example incremental grout volume log where the number of pump strokes are recorded for every 5ft increment of auger extracted. The incremental grouting log should be read from the bottom up.

Table 4.2 Manual grout volumes recorded on 5ft increments

Depth Interval			Pump Count		Grout Volumes		
			Incremental	Cumulative	Incremental		Cumulative
(ft)			(strokes)	(strokes)	Actual (cu. ft.)	% Theor.	Actual (cu. ft.)
0	to	5	16	138	12.57	142%	108.43
5	to	10	16	122	12.57	142%	95.86
10	to	15	18	106	14.14	160%	83.29
15	to	20	14	88	11.00	124%	69.14
20	to	25	17	74	13.36	151%	58.14
25	to	30	14	57	11.00	124%	44.79
30	to	35	14	43	11.00	124%	33.79
35	to	40	29	29	22.79	258%	22.79
Total:			138		108.43	153%	

FDOT requires both methods of grout volume monitoring to be within 3% of each other (FDOT, 2022). For each pile analyzed, a new dataset was created that contained the cumulative pumped grout from the incremental grout log above (Table 4.2) and the equivalent AME flow meter recorded grout volume. Table 4.3 presents an example comparison where the VLOOKUP function in excel was used to find the corresponding flow meter recorded grout volume at each 5ft depth increment. The adjusted cumulative pump stroke volume column includes the initial head volume (Vol 2) that is not included in the incremental grout log, but which needs to be added to compare to flow meter measurements.

Table 4.3 Combined pump stroke and flow meter volume dataset

Depth	**Pump Strokes**		**AME Flow Meter**
Interval	**Cumulative Vol.**	**Adj. Cumulative Vol.**	**Cumulative Vol.**
[ft]	**[ft^3]**	**[ft^3]**	**[ft^3]**
0	1219.8	1333.4	1322.2
5	1184.3	1297.9	1295.6
10	1147.4	1261.0	1258.9
15	1104.8	1218.4	1216.0
Table Condensed...			
115	196.0	309.6	306.3
120	147.7	261.3	258.5
125	99.4	213.0	210.6
130	46.9	160.5	161.6

The flow meter volumes were plotted against the pump stroke volumes (columns 3 and 4 from Table 4.3) and a best-fit linear regression was performed. The slope of the best-fit line represents the ratio of flow meter over pump stroke volume. Figure 4.1 shows an example of near perfect agreement between both grout volume accounting methods. Conversely, Figure 4.2 shows a best-fit line with a slope of 0.92, showing that for every 100cuft of grout measured by counting pump strokes, the flow meter recorded 92cuft. This represents a 7.8% error (if the pump stroke method is assumed to be correct), exceeding the 3% FDOT specified maximum. The term disagreement will also be used in lieu of error when a difference cannot be attributed to either volume measurement method.

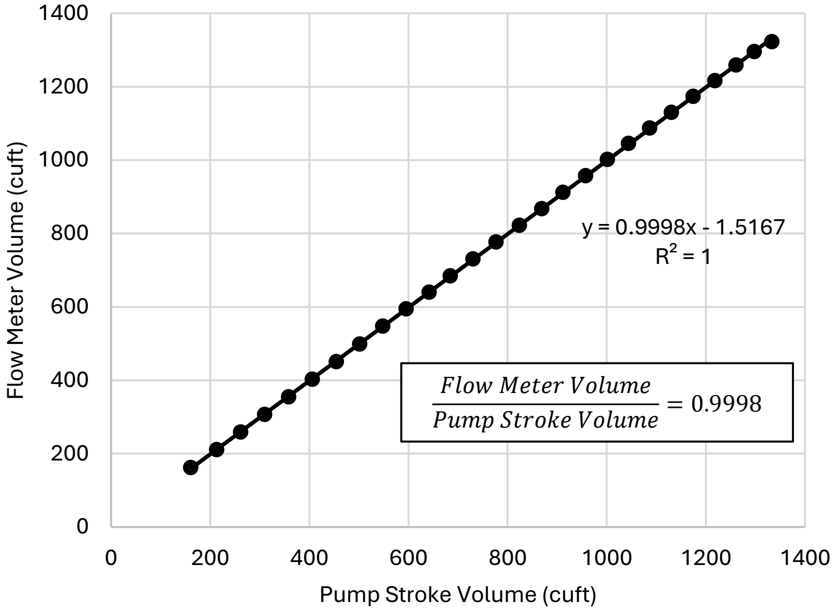


Figure 4.1 Both volume accounting methods (pump stroke counting and flow meter) showing strong agreement

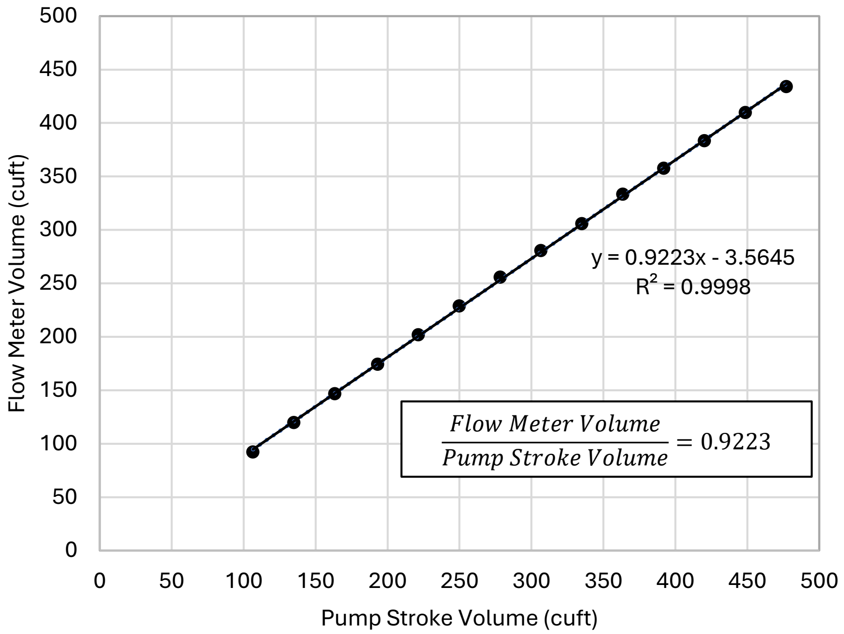


Figure 4.2 Pump stroke volume vs. AME flow meter volume showing 7.8% disagreement in tracked grout volume

Comparison of grout volume as measured using pump strokes and AME recorded flow meter data was performed for 651 auger cast piles from the I-395/SR 836/I-95 project. Figure 4.3 presents the AME flow meter volume/pump stroke volume ratio for all 651 piles, showing 64% of piles analyzed to be outside of the 3% agreement criteria. The flow meter vs counted pump stroke volume relationships for each pile showed high values for the coefficient of determination, R^2, (like Figures 4.1 and 4.2) ranging from 0.9863 to 0.9999 with 97% at 0.999 or higher. The strong linearity of the trends from all piles suggests both volume measurement methods were tracking volume reliably, and a calibration error from one or both of the two measurement methods is the only explanation for the discrepancies. The average R^2 was 0.9995, and the coefficient of variation (COV) was 0.003. To add perspective, the COV value for the ultimate strength of structural steel bolts is 0.02, almost an order of magnitude more variable (Galambos, 1981).

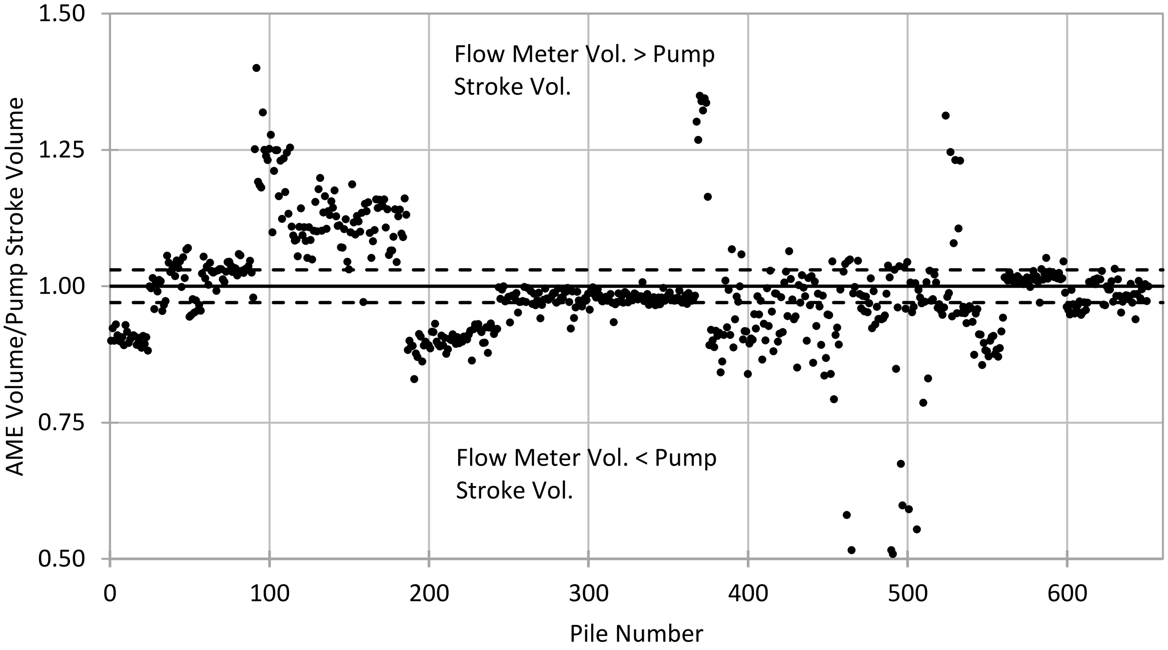


Figure 4.3 AME flow meter/pump stroke volume ratios for 651 auger cast piles where the dashed black lines represent the upper and lower bounds of the 3% disagreement criteria

The instances of disagreement between the two separate means of grout volume monitoring are difficult to evaluate as one or both methods may be calibrated improperly. To better evaluate each method, pump strokes per concrete truck volume were recorded during the construction of the last 52 piles (599 - 651) presented in Figure 4.3. The limitation of this approach then falls on knowing the true volume of the truck; here the mix ticket specified volume was used. A total of 158 truck volumes were available, where the average pump strokes per truck was 134. To evaluate pump strokes, the number of strokes per truck was multiplied by the pump stroke calibration constant (volume/stroke) found during the FM 5-612 calibration procedure. The mix ticket specified truck volume was divided by the calculated pump stroke volume, where a ratio of 1 represents perfect agreement. Figure 4.4 shows the distribution of truck volume / pump stroke volume ratios.

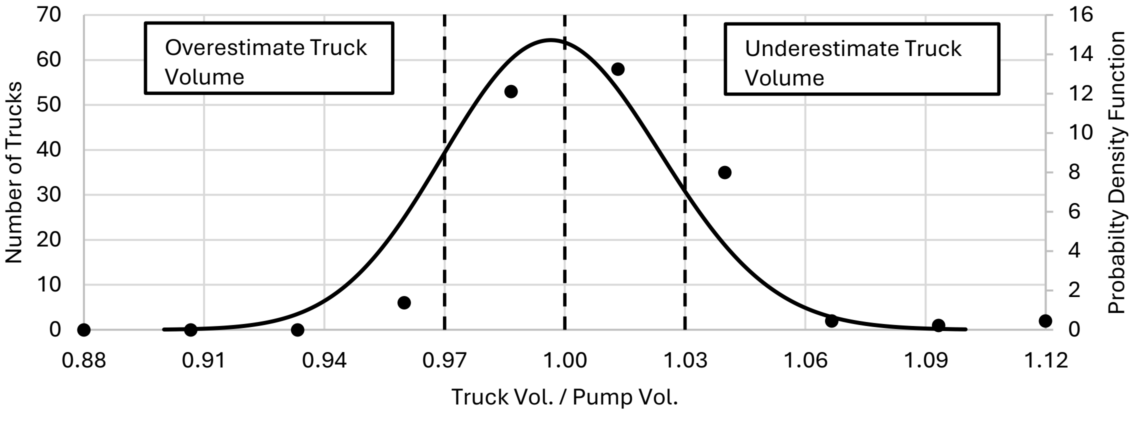


Figure 4.4 Truck volume over pump stroke calculated truck volume ratio for 158 trucks

The dashed black lines at 0.97 and 1.03 represent the ±3% criterion specified for the pump stroke to flow meter volume agreement. While there is no requirement for agreement to larger truck volumes, this ±3% was incorporated as a reasonable reference. To obtain an equivalent flow meter volume, the number of strokes per truck was multiplied by the pump calibration as before, further multiplied by the previously determined flow meter/pump stroke volume ratio, like those in Figures 4.2 and 4.3. Figure 4.5 presents the distribution of truck volume to flow meter volume ratios for the same 158 truck volumes. Log normal distributions were fitted to both data sets (Figures 4.4 and 4.5) where the average overprediction of mix ticket truck volume by pump stroke counting and flow meter records was 0.31% and 2.07%, respectively. Furthermore, 74% of the pump stroke volumes and 59% of flow meter volumes were within 3% of the truck volume. Comparison of grout records to larger truck volumes indicate pump stroke counting to better match truck volumes.

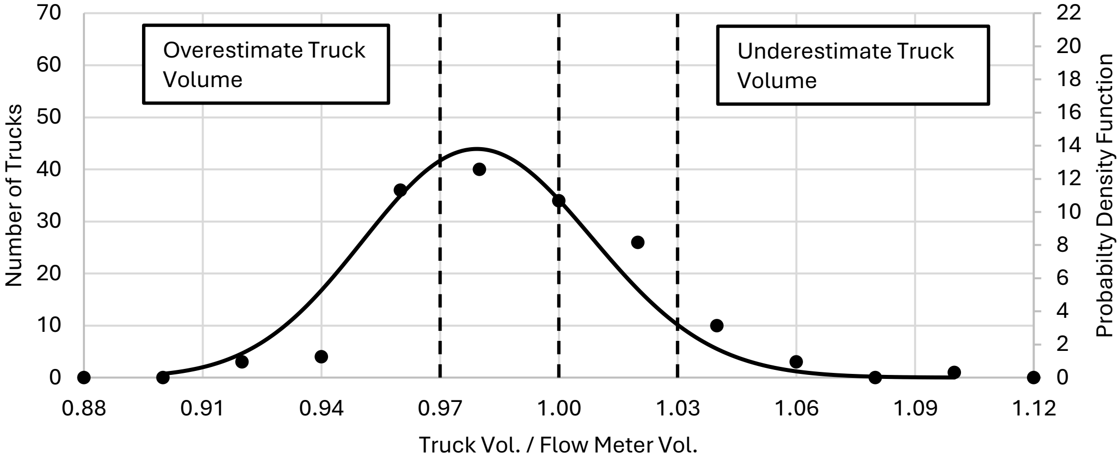


Figure 4.5 Truck volume over flowmeter calculated truck volume ratio for 158 trucks

4.3 Efforts to Back-calculate Statistical AFF Values

For a subset of 48 auger cast piles, as-built dimensions were recorded at the cut-off elevation where soil surrounding the piles was excavated to make room for the pile cap. The piles were then cut-off to expose the reinforcing steel that will tie into the pile cap. Given the relationship between locally measured pile temperature and size established by thermal integrity testing, the as-built pile size and measured temperature (both at the cut-off elevation) allow for the evaluation of an AFF selection and subsequent final pile volume. To start, the total pile volume is defined as the initial head volume (2) plus the incremental volume (3) plus a portion of volume after grout return is observed calculated in equation (4.1). An initial site specific AFF of 0.85 was selected for all 48 piles.

$$V_{pile} = Volume_2 + Volume_3 + AFF * \pi * r^2 * L_{return} \tag{4.1}$$

where:

V_{pile} = *final pile volume (cuft.)*
$Volume_2$ = *initial head volume (cuft.)*
$Volume_3$ = *incremental volume (cuft.)*
AFF = Auger Fill Factor
L_{return} = *return depth (ft.)*

From the total pile volume, average radius can be calculated as follows:

$$R_{avg} = \sqrt{\frac{V_{pile}}{\pi * L}} \tag{4.2}$$

where:
V_{pile} = *final pile volume (cuft.)*
L = pile length (ft.)

There are two approaches to developing the temperature to radius (T-R) constant (T_{zero} and T_{soil}). For this analysis, the T_{soil} approach was selected where the local soil temperature of 77°F was used. The T-R constant correlates local temperature variation to changes in pile size and is calculated as follows:

$$TRC_{soil} = \frac{R_{avg}}{T_{avg} - T_{soil}} \tag{4.3}$$

where:
TRC_{soil} = *temperature / radius constant*
R_{avg} = *average pile radius (in)*
T_{avg} = *average pile temperature (°F)*
T_{soil} = *local soil temperature (°F)*

The T-R relationship is then used to predict the radius of the pile at the cutoff elevation, where field measurements were taken after excavation of the top of pile. If the temperature at the cutoff elevation is larger than the average pile temperature, this corresponds to a larger than average pile radius. The predicted pile radius based on thermal data is calculated as follows:

$$R_{cutoff-prediction} = TRC_{soil} * (T_{cutoff} - T_{soil}) \tag{4.4}$$

where:
TRC_{soil} = *temperature / radius ratio*
T_{cutoff} = *pile temperature at the cut-off elevation (°F)*

This calculation assumes the measured temperature to pile radius relationship is linear, which is a simplification shown to be a reasonable approach for variation in predicted radius up to 6in (Mullins & Johnson, 2017). The true T-R relationship is hyperbolic as seen in Figure 4.6.

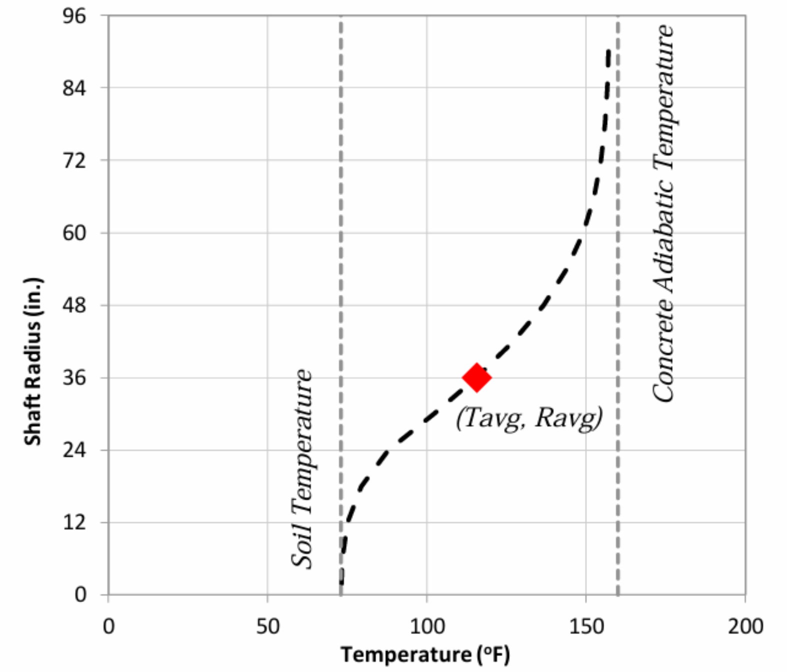


Figure 4.6 Temperature / radius (T-R) relationship where a linear approximation is used near the inflection point (Mullins & Johnson, 2017)

The predicted pile size at the cutoff elevation is compared to the as-built field measurements collected. If in disagreement, the AFF used to calculate pile volume in equation 4.1 is iterated until the following condition is satisfied:

$$R_{cutoff-measured} = R_{cutoff-prediction} \tag{4.5}$$

Once the condition in equation (4.5) is satisfied, the back-calculated AFF for the 48 piles was recorded and a histogram created. Figure 4.7 shows the distribution of computed AFF values and a fitted normal distribution, where the average and standard deviation were 59.7% and 8.97%, respectively. Note an empty auger in this case represents 13% of the nominal auger volume (AFF = 0.13). To obtain AFF as a percentage, multiply by 100.

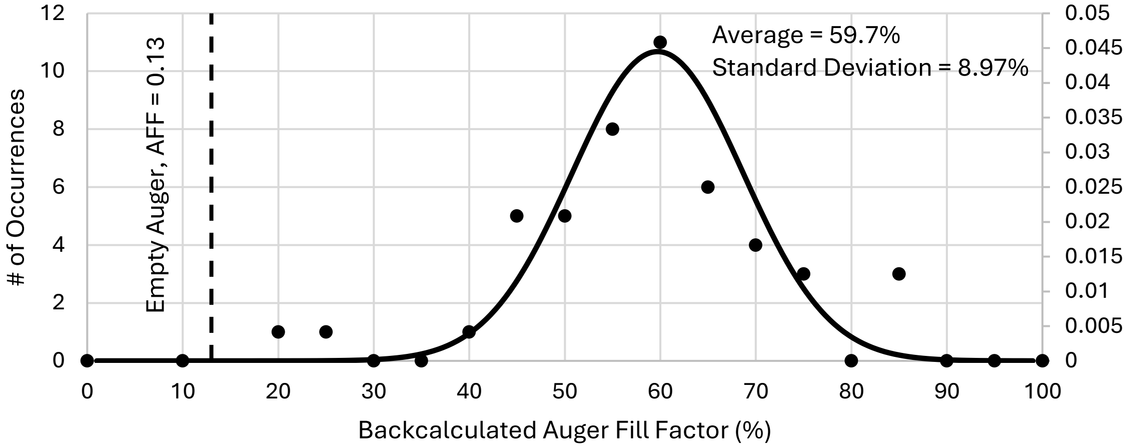


Figure 4.7 Distribution of back-calculated AFF values and normal distribution fit [data from I-395 piers 4-15, 4-16, 5-15L, 5-15R, 5-16L, 5-16R]

As previously mentioned, the original analysis used an AFF of 0.85, resulting in an overprediction of measured pile diameter for all 48 piles, shown as hollow circles in Figure 4.8. Similar to previous plots, the one-to-one line represents perfect agreement between measured and predicted pile size values. The average back-calculated AFF value of 0.597 (Figure 4.7) was selected and the $R_{\text{cutoff-prediction}}$ re-computed. All back-calculated values fell within a realistic range of a partially to completely full auger. The predicted pile diameters with a more appropriate AFF selection are shown as solid triangles in Figure 4.8.

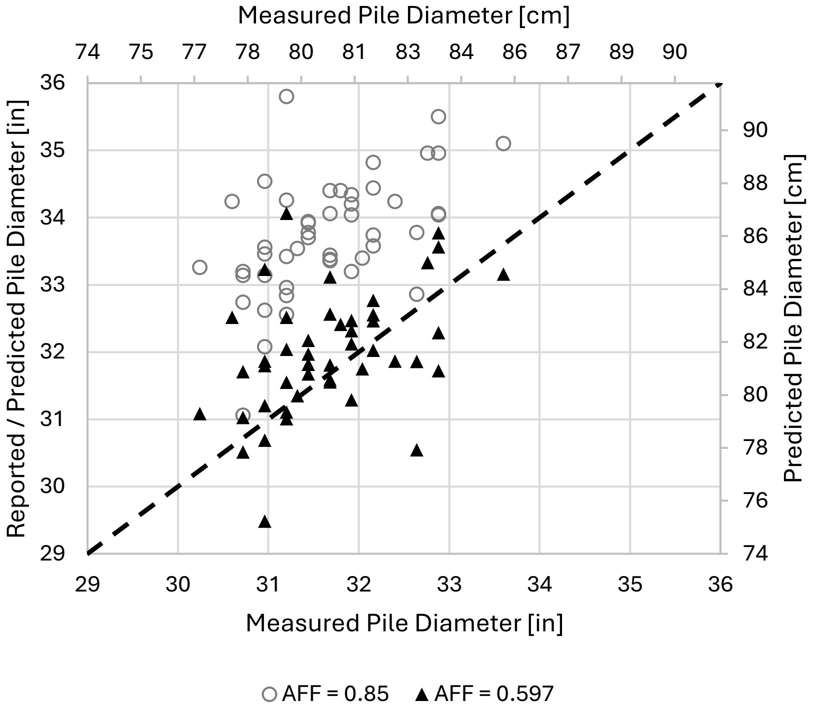


Figure 4.8 Reported pile diameter using default AFF = 0.85 and pile diameter using back-calculated AFF of 0.597

A more appropriate AFF selection resulted in more accurate pile size predictions, giving credence to its use when calculating volume 4 and subsequent pile volume. While this procedure of back-calculating a more appropriate AFF value worked well within this subset of 48 piles, a larger set of 210 auger cast piles showed the tendency to produce unreasonable AFF values. An unreasonable AFF value is either below 0.13 (empty auger) or above 1.0 (completely full auger).

When AFF was back-calculated across 128 auger cast piles, 16 were above AFF = 1.0 and 88 were below an empty auger fill, AFF = 0.13. The average AFF of the set was 0.26, nearly an empty auger. The presence of unreasonable back-calculated AFF values may indicate an error in final pile volume, calculated as the sum of volumes 2, 3, and a portion of volume 4. Incorrect final pile volume could be a result of flow meter or pump stroke accounting errors, grout volume filling voids and not contributing to final pile volume, or other unknown volume accounting errors. For example, if at any point during pile installation, grout was filling a void rather than contributing to the pile, the true pile volume would be less than calculated using equation (4.1). To ensure agreement between the predicted pile size at the cut-off elevation and that measured, the pile volume would need to be decreased by lowering the AFF, even below the point of an empty auger (AFF = 0.13).

Furthermore, difference in near-surface temperature has the potential to further complication the use of AFF back-calculation. The soil surrounding a pile group is excavated to make room for the pile cap. Within the I-395 project piles analyzed here, only 2 to 12ft of soil is removed to reach the cut-off elevation. The location where as-built pile measurements are taken may present temperature affected by the seasonal variation in soil temperature near the surface. This effect and its potential to influence AFF back-calculation is discussed in section 4.4.

4.4 Potential for Air Temperature Effects

The back-calculation of AFF was performed by ensuring agreement between the predicted and measured diameter at the cut-off elevation. The depth of the pile cut-off point ranged from 2ft to 12ft below the ground surface. During the analysis of thermal integrity testing data, the soil temperature is assumed to be constant along the length of the pile based on the geographical location of the project site and the corresponding soil temperature. All piles analyzed were constructed in Miami, FL where the constant soil temperature at depth is 78^{o}F. Figure 4.9 shows the isothermal ground temperature lines across the United States.

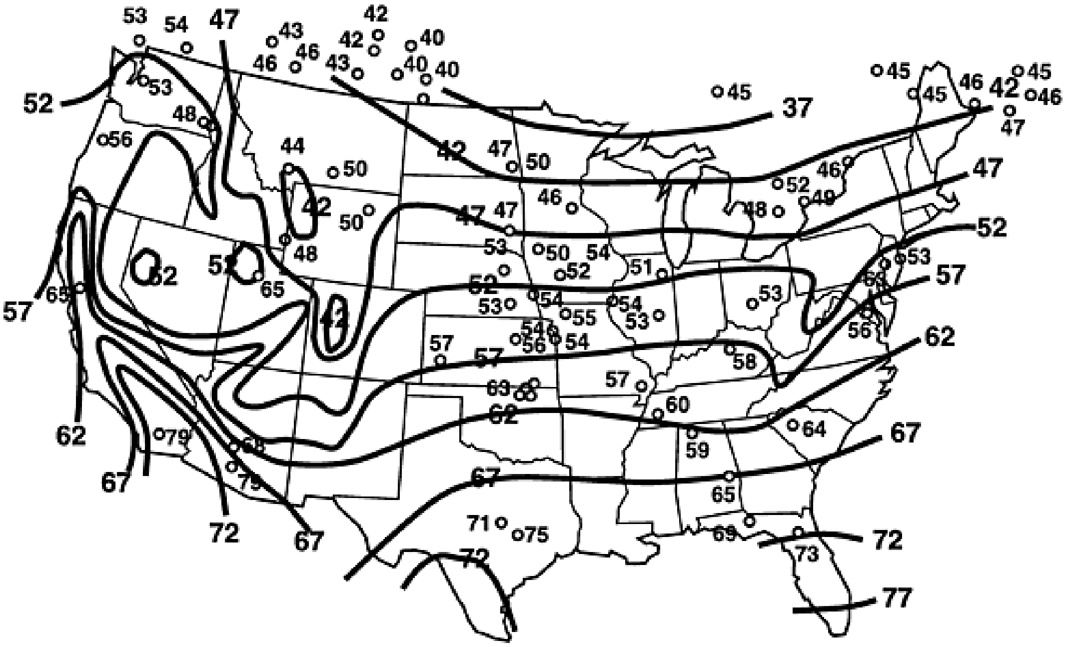


Figure 4.9 Ground temperature isothermal lines map of the United States (Olgun, 2015)

While soil temperature is generally regarded as constant, near surface temperatures have been shown to fluctuate seasonally. Figure 4.10 shows sample ground temperature measurements taken in Odessa, FL where the magnitude of seasonal variation increases closer to the surface. The soil temperatures throughout the year begin to converge at a depth of 8ft, however, the cut-off depths of many of the auger cast piles analyzed are above this point. It should also be noted that the soil temperature is phase shifted from the observed air temperature, the degree to which depends on the soil depth. For example, the hottest soil temperature at a depth of 6ft may occur 2 to 3 months after the hottest daily average air temperature.

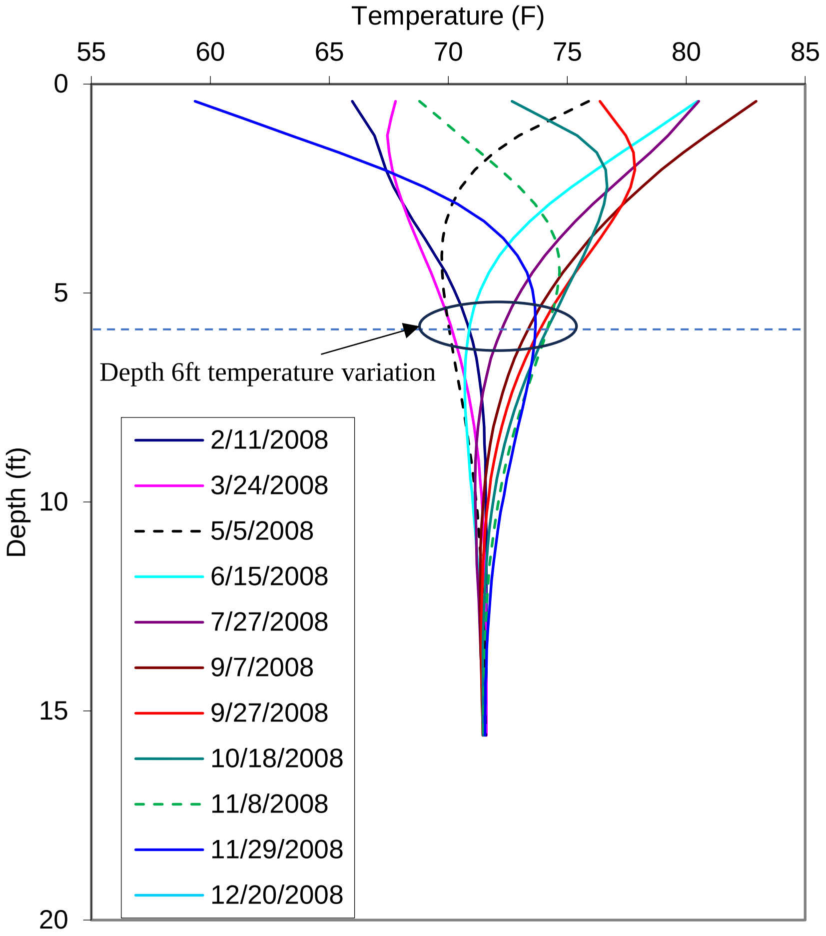


Figure 4.10 Ground temperature variation as a function of depth (Mullins et al., 2009)

Analysis of all auger cast piles with as-built dimensions showed the tendency for over-prediction of as-built pile diameter in the hotter months of the year. Figure 4.11 shows the pile diameter bias (measured/predicted) for all 334 piles with available as-built measurements constructed between March 2020 and April 2021 (13 months). A bias value greater than 1.0 indicates an underprediction of pile size and a bias less than 1.0 an overprediction. Figure 4.11 also presents the ground temperature as a deviation from the average annual soil temperature, positive values representing higher than average soil temperature. When soil temperature at a depth of 6ft is greater than average, thermal integrity testing estimations of pile size showed a tendency to overpredict the true pile size at the cut-off elevation. It should be noted that onsite soil temperature measurements from Miami, FL were unavailable and those presented in Figure 4.11 are presented as an indication of soil temperature variation with depth (data collected in Clearwater, FL; Mullins et al., 2009).

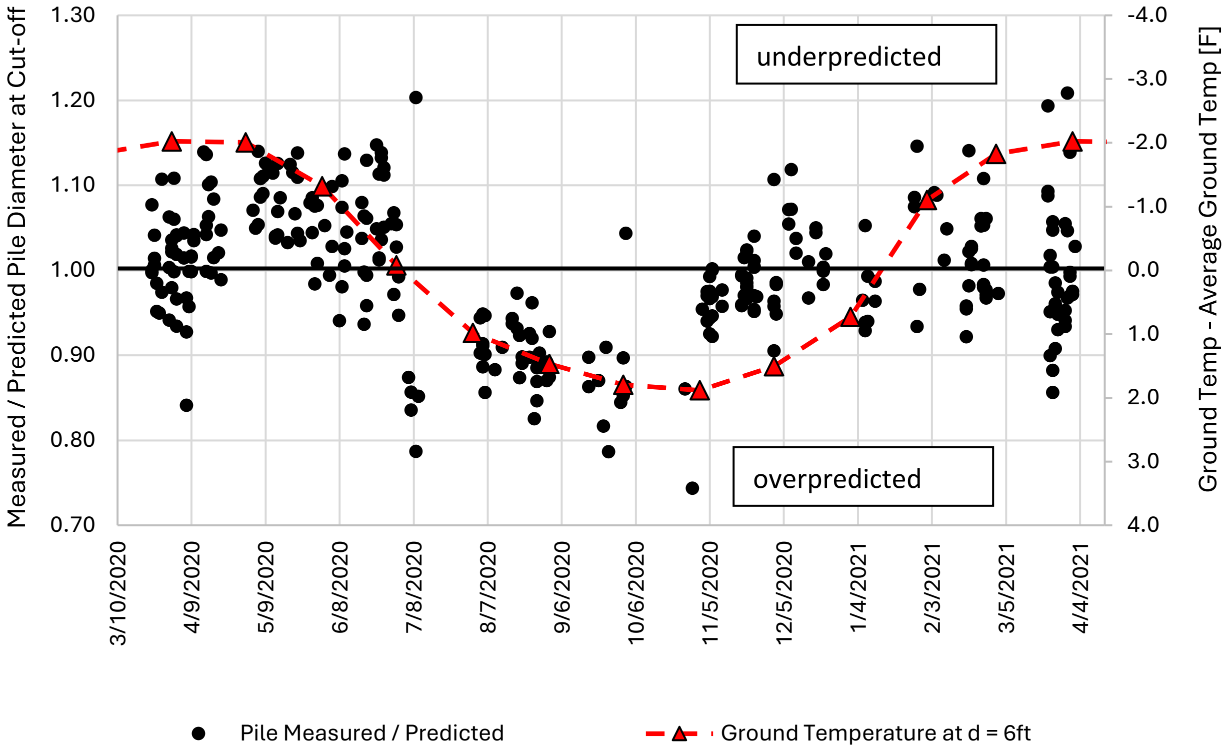


Figure 4.11 Measured over predicted pile size over time (334 piles cutoff depth 2 to 12ft)

This indicates that the temperature measurements at the cut-off location may be warmer than the average pile temperature due to the reduced ability of the near-surface soils to diffuse heat away from the pile. The artificially increased temperature at the cut-off elevation makes the pile to be calculated larger through use of the T-R relationship when in reality, the upper portion of the pile may be no larger than the average pile size. When back-calculating AFF, the measured and predicted pile size are matched. If the cut-off temperature is larger than average, the total pile volume must be decreased to ensure agreement, accomplished by low or even negative AFF values, far below the 0.13 lower limit. The observation of negative AFF values largely occurred in the hottest months of the year.

These findings suggest that AFF back-calculation works well when piles are installed properly, grout volume is correctly tracked, all tracked grout volume is truly contributing to the final pile volume (i.e., no void filling), and soil temperature is uniform as was the case with the 48 pile sample set. It should be noted that as-built measurements taken deeper would be less subject to seasonal temperature variation. Determining a more appropriate AFF post-construction will consider all variables contributing to final pile volume, which is not reasonable in all cases. Furthermore, AFF back-calculation requires as-built measurements taken at the cut-off elevation after pile excavation for the pile cap, which is not common practice for all piles.

Across all piles, back-calculated AFF values ranged widely including many outside of the physical limitations of auger fill (i.e., less than an empty auger or more than a full auger). When the auger fill at the time of construction is unknown, the use of back-calculation should carefully consider the depth to the cut-off elevation where as-built measurements are taken and the current soil temperature profile based on the time of year. AFF back-calculation was attempted as a means of compensating for the fact that no visual estimations of auger fill were conducted during construction. However, visual estimations of AFF on a per-pile basis during auger extraction is recommended as the best approach when determining final pile volume, discussed in the following section.

4.5 Visual Estimation of AFF

The use of an auger fill factor is established as a means to better estimate the final pile volume. It is important to note that many drill rigs have scrapers to clean the augers and any estimation of AFF should be performed below the scraper prior to the removal of soil cuttings from the auger flights. Evaluation of field photos during auger extraction/grouting identified three unique modes of soil adhesion to the auger. The soil can cling to the center stem, sit on the auger flights, or be a combination of both (i.e., a hybrid cling mode). Figure 4.12 presents examples of all three soil cling modes.

Figure 4.12 (from L to R) soil cuttings adhere to auger stem, soil cuttings sit on auger flights, and an example of a hybrid soil cling mode

Regardless of the soil adhesion mode, visual inspection of photos of the auger during extraction provide a means of post-construction AFF estimation. Figure 4.13 shows a series of images taken of the extracted auger at every 10ft increment. It should be noted that the first image in the series (denoted 82ft) represents the start of grouting/auger extraction. The regions of the auger tinted red represent the soil cuttings and auger while the green tint represents a full cylindrical volume with a diameter equal to the nominal pile diameter.

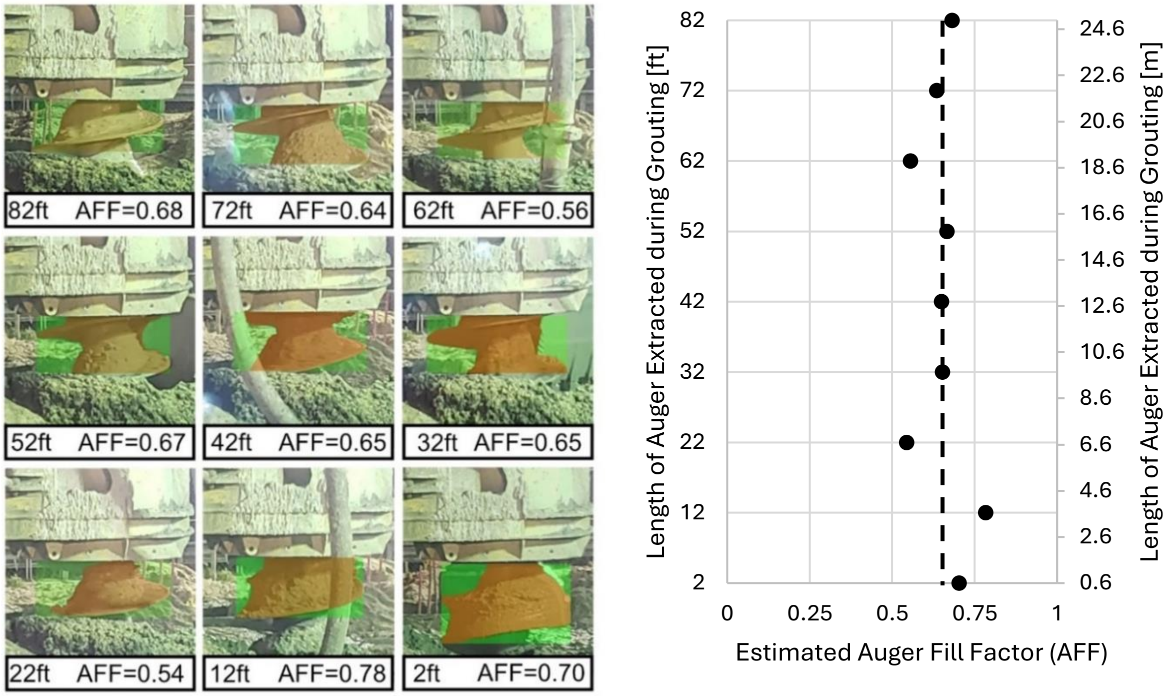
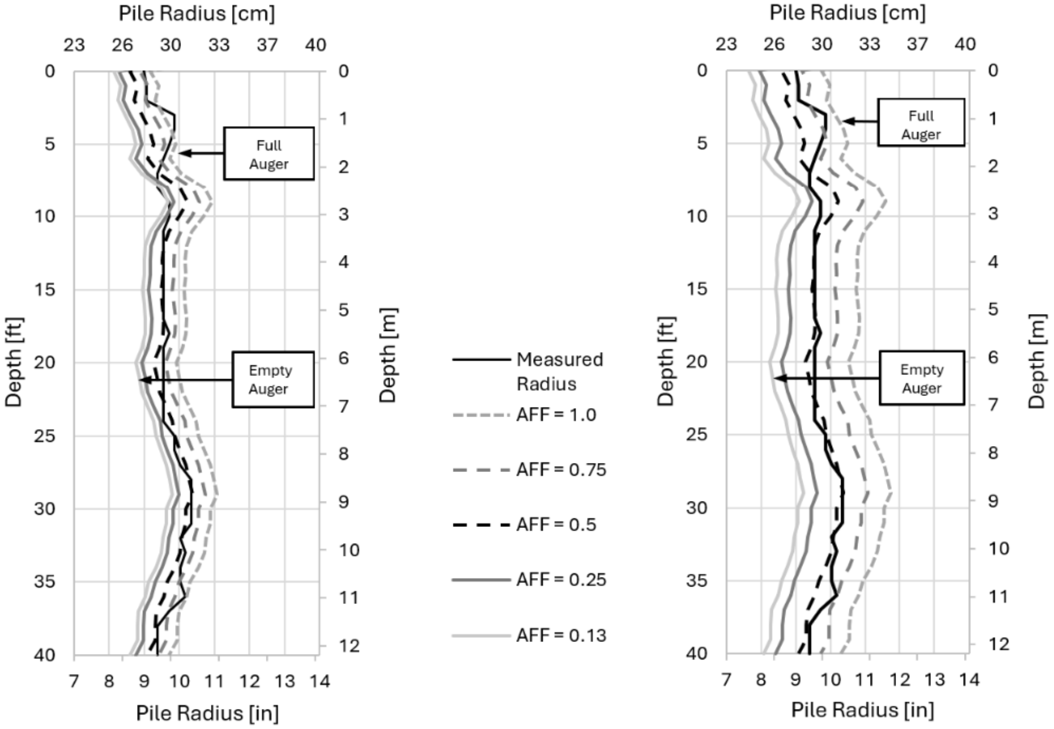


Figure 4.13 (left) Photo discrimination methods used to estimate AFF during auger extraction (right) estimated AFF at each length increment of extracted auger

An average AFF of 0.65 was observed and found to be uniform along the length of the extracted auger, which does not always need to be the case. If nonuniform, the most representative section of the auger (i.e., that which is in the excavation at the point of grout return) should be used to estimate AFF.

Field photos taken during auger extraction indicate that even within the I-395 project site, auger fill ranges from nearly full to nearly empty. This observation highlights the value of recording AFF on a per pile basis. Sample visual estimation guides were developed to provide a means of more accurately recording AFF. While this will not guarantee accurate pile volumes, recording AFF on a per pile basis will reduce volume uncertainty and lead to more representative pile volumes.

It is envisioned that estimations of AFF to the nearest 20-25% would be sufficient, smaller percentages will be more difficult to determine and result in minimal changes to the overall pile diameter approximation. Figure 4.14 shows the effect of changing AFF when determining the Volume 4 contribution to the overall pile size as predicted by thermal integrity testing. Again, the AFF only affects the last phase of grouting and yet the effect is considerable. In this case, the true return depth was 13ft (32.5% of the pile length), however, deeper return depths also increase the Volume 4 contribution and any associated uncertainty. Figure 4.14 (left) shows the same effect on predicted pile size if the return depth increased from 13ft to 26ft for a 40ft pile (from previous FDOT/DFI study). The full range of predicted pile diameters (AFF from 0.13 to 1.0) varied from 26.4 to 28.5in and 25.5 to 29.6in for the short and long return depth, respectively. Here the solid black line represents the measured dimension of the extracted pile, agreeing most closely with the pile volume when an AFF of 0.5 is selected.



Return Depth 3.96m (13ft)

Return Depth 7.92m (26ft)

Figure 4.14 Effect of AFF selection and grout return depth on predicted pile size

Note the percentage of possible soil volume that can be held by an auger is not the same as AFF as a completely empty auger represents the volume of steel and the hollow stem relative to the completely full cylindrical prism. The pitch of the flights, flight thickness, and outer diameter of the center stem affect the empty auger AFF value. A preliminary survey of auger manufacturers indicates the empty auger AFF value would be between 0.11 and 0.22 where flight thickness, auger pitch, and outer diameter of the center stem ranged from 0.75-1in, 15-20in, and 8-12in, respectively. Augers are typically made to order based on local geology, drilling torque, anticipated pile depth, and contractor preferences. Equation (3.11) is presented to compute the empty auger fill factor (AFF$_0$).

$$AFF_0 = \frac{{\emptyset_{STEM}}^2(p-t) + t{\emptyset_{AUGER}}^2}{p{\emptyset_{AUGER}}^2} \tag{3.11}$$

where:

$AFF_0 = empty\ auger\ fill\ factor$

$\emptyset_{AUGER} = nominal\ auger\ diameter\ (in)$

$\emptyset_{STEM} = outer\ diameter\ of\ auger\ center\ stem\ \ (in)$

$p = auger\ flight\ pitch\ (in)$

$t = auger\ flight\ thickness\ (in)$

example calculation:

$\emptyset_{AUGER} = 30in$

$\emptyset_{STEM} = 8.5in$
$p = 15in$
$t = 0.75in$

$$AFF_0 = \frac{(8.5in)^2(15in - 0.75in) + (0.75in)(30in)^2}{(15in)(30in)^2} = 0.126$$

Field estimation aids were developed for both the soil stacking and center cling means of soil adhesion, seen in Figures 4.15 and 4.16, respectively.

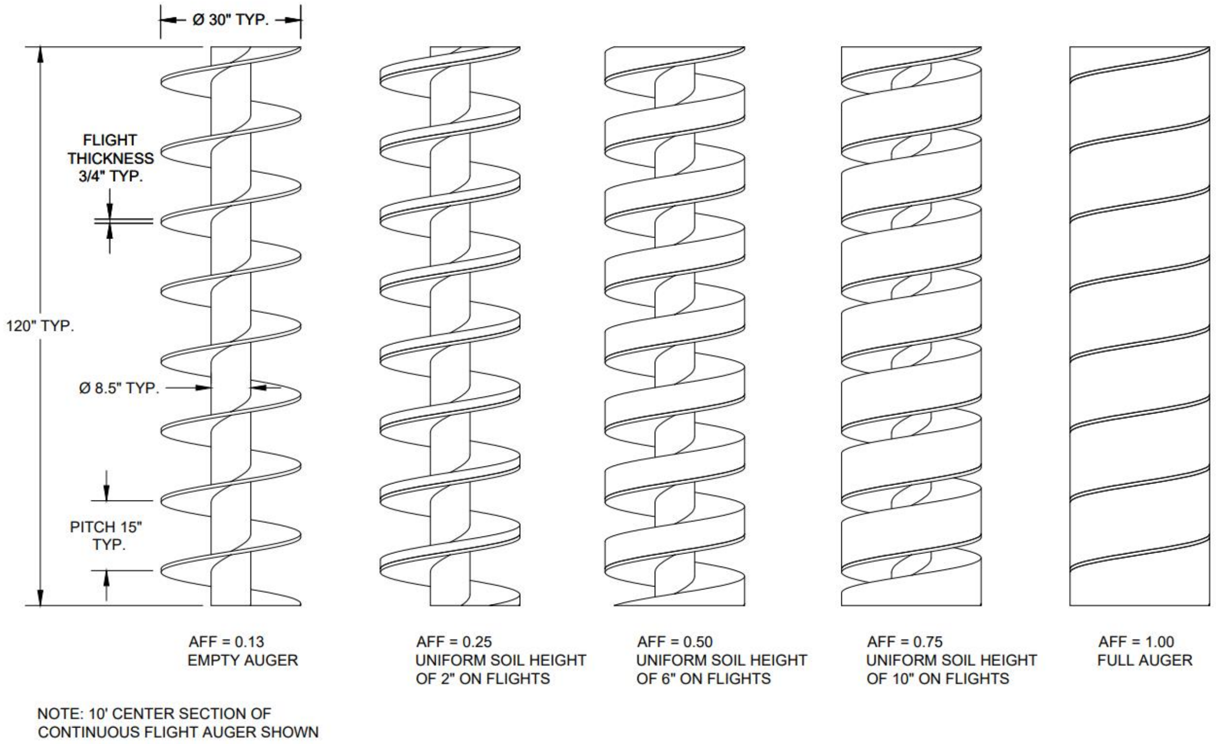


Figure 4.15 Visual aid to identify AFF when soil stacks on auger flights

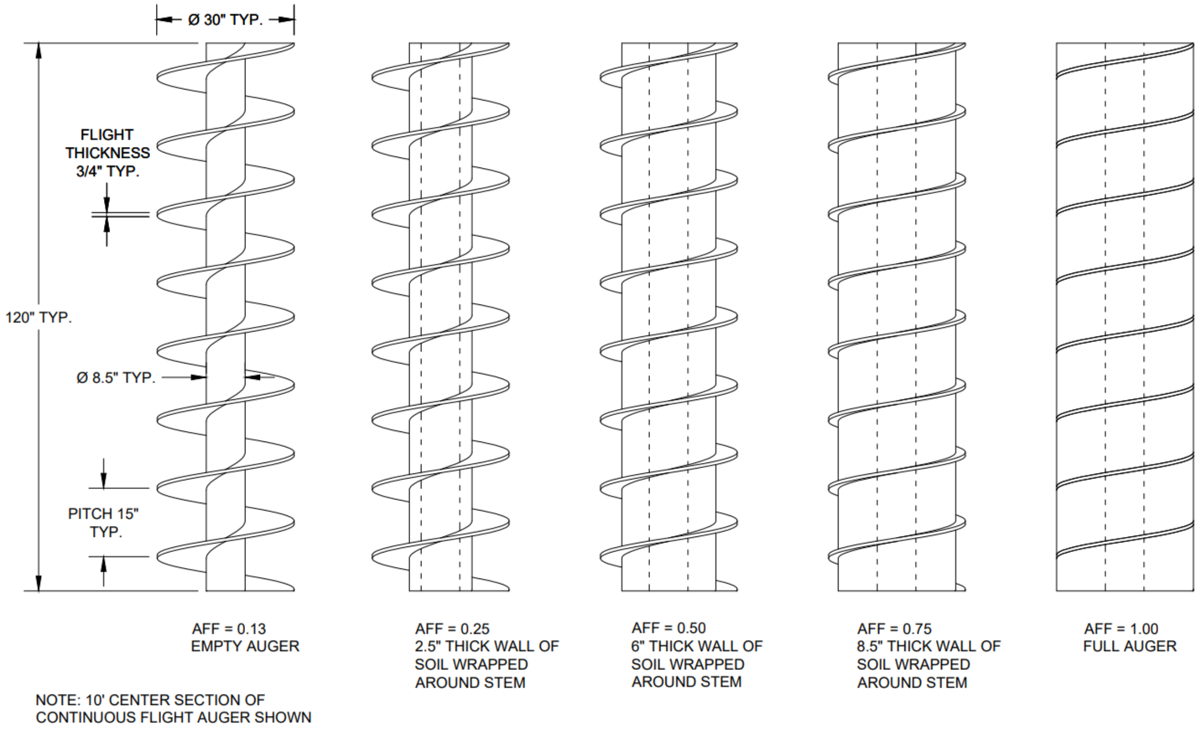


Figure 4.16 Visual aid to identify AFF when soil clings to center stem of auger

A field book of common auger sizes from various manufacturers is envisioned to allow inspectors to better estimate AFF for a wide range of auger sizes and degrees of soil fill. Furthermore, given an auger design unique to a jobsite, 3D models can easily be adjusted to develop special estimation guides.

Chapter Five: Summary and Conclusions

5.1 Summary

Auger cast piles have historically been used for private industry applications but are increasingly used for publicly funded infrastructure projects. The I-395/SR 836/I-95 expansion project is the first and largest use of auger cast piles in the state of Florida for support of major bridges. All of the thermal testing results, installation logs, Automated Measuring Equipment (AME) data, and available as-built pile dimensions from the I-395 project were collected to better assess current means of estimating final pile volume and provide recommendations for improved pile integrity evaluation.

The installation of auger cast piles involves the use of a continuous flight auger drilled to depth in one uninterrupted motion followed by continuous grouting from the pile tip to the ground surface. The act of removing and reinserting the auger was defined as a re-stroke. Re-stroking can occur during drilling or grouting, leaving the excavation temporarily unsupported and creating the opportunity for sidewall collapse, soil relaxation, and/or grout contamination. Re-stroking also changes the AFF due to soil removal above ground that is not replaced when reinserted and/or during grouting. To evaluate the frequency of re-stroking, AME records for 386 piles provided the auger tip depth as a function of time, separated into drilling and grouting operations. Of the 386 auger cast piles analyzed, AME installation records showed 59.6% of piles experienced some form of auger re-stroking. This should be scrutinized by FDOT for stronger inspection specifications.

During pile installation, pumped grout volume is recorded by AME on-board the drill rigs via a magnetic flow meter. These flow meters measure the induced voltage by a flowing conductive fluid (grout) to determine the flow velocity, converted to flow rate with a known cross-sectional area. Alternatively, grout volume can be calculated by multiplying the number of recorded pump strokes by the pump calibration (cuft/stroke). Current installation specifications (FDOT, 2023) require both volume accounting methods to be within 3% of one another. Flow meter and pump stroke records for each pile were combined where the corresponding volume at each increment of pile tip depth was noted. A linear fit was applied to pump stroke vs. flow meter volumes, where a slope of 1.0 represents perfect agreement between both methods. Analysis of the installation and AME records of 651 auger cast piles showed 64% to be outside the 3% agreement criteria. While during the installation of most piles, flow meter and pump strokes records did not match, every pile showed a strong coefficient of determination (R^2), indicating both methods were tracking grout volume properly and a calibration error from one or both explains the disagreement in measured grout volume.

In an effort to pinpoint which of the two volume accounting methods had an inaccurate calibration value, the number of strokes required to empty each concrete truck were recorded across 52 piles. This resulted in 158 truck volumes and corresponding pump stroke counts, which showed volume measured from pump strokes aligned more strongly with truck volumes as recorded on the mix tickets. It should be noted that during the installation of these 52 piles, pump strokes and flow meter volume measurements showed better agreement than the average as determined across all 651 piles. While the truck volumes and number of pump strokes required to empty each truck were not available for all 651 piles, this analysis highlights the value of having three independent grout volumes measurements from which to evaluate.

For a subset of 48 piles, as-built measurements were recorded at the cut-off elevation which allowed local comparisons between predicted pile size and measured pile size. Pile diameter was predicted using the measured temperature at the cut-off elevation and the temperature to radius (T-R) relationship established through thermal integrity profiling. The T-R relationship requires the final pile volume which is the sum of the initial head volume (vol. 2), the incrementally pumped volume (vol. 3), and a portion of the finishing volume once grout return is observed (vol. 4). The quantity of volume 4 depends on the fullness of the auger within the excavation at the point of grout return, estimated using the Auger Fill Factor (AFF). A generic AFF of 0.85, assigned to all 48 piles, resulted in an over-prediction of pile size across the board.

Using the recorded as-built dimensions and the grout volume records, a more appropriate AFF was back-calculated. When a new AFF of 0.597 was applied to all 48 piles, the resulting size predictions were much closer to the true pile size, as measured at the cut-off elevation. However, when this approach was applied across a larger set of auger cast piles, it showed the tendency to produce AFF values above and below physical auger fill limits (i.e., less than an empty auger or greater than a full auger). As previously noted, grout volume accounting errors can arise when installation procedures are not adequately followed, for example when re-stroking occurs, resulting in a discontinuous pile installation or when large disagreement exists between both volume accounting methods. These errors, the magnitude of which are unknown, are accounted for through back-calculation of an AFF to match measured and predicted pile size. AFF back-calculation can be further complicated by seasonal variation in near-surface soil temperatures, affecting pile size predictions at the cut-off elevation where as-built measurements were available.

While back-calculation of AFF may not be appropriate for every auger cast pile, visual estimation of AFF during the construction of every pile provides a more accurate means of determining final pile volume. An equation to calculate the baseline AFF of an empty auger based on the nominal auger diameter, diameter of the hollow stem, flight pitch and flight thickness was presented. Three modes of soil adhesion to the auger were identified and 3D CAD models for the two primary modes of soil adhesion (center cling and flight stacking) were used to create visual aids. Pile inspectors can use visual aids to quickly estimate AFF of the auger in the hole once grout return is observed. These models can easily be expanded to create an entire field book of common auger sizes and AFF estimation visuals. Inspector recorded AFF values on a per pile basis remove the uncertainty associated with using a site-specific / generic value.

5.2 Conclusions and Recommendations

The analysis performed on auger cast pile installation records provided insight into the variables affecting pile volume accounting and subsequent pile integrity evaluation. Based on the findings of this study, the following recommendations are made:

- Every effort should be made to reduce the frequency of re-stroking during auger cast pile construction. The absence of temporary/permanent casing and support fluid (as is common in drilled shaft construction) makes the presence of the soil-laden auger crucial for maintaining excavation stability. Ideally, the rotation and penetration rate of the auger during drilling should promote a full auger. This recommendation, made by (Brown *et al.,* 2007), is supported by the findings of this study.

- Current specifications require pump stroke calibration into a 55-gallon drum (FM 5-612) before the installation of demonstration piles, every two piers/bents or more frequently at the Engineer's discretion (FDOT, 2023). However, calibration specifications are less prescriptive for magnetic flowmeters where flowmeter replacement is recommended when the volume monitored by both methods varies more than 3%. Given the large number of piles showing unacceptable disagreement between the two volume accounting methods, plotting flow meter and pump stroke volumes during the production grouting of every pile is recommended to ensure both agree across a larger pumped volume.

- FDOT specifications further suggest that if a flowmeter records a volume 3% greater than the pump stroke volume, the stroke counting method should be used to determine pile acceptance (FDOT, 2023). This approach is conservative and is supported by the findings of this study. For a subset of 52 piles where the number of strokes per concrete truck were recorded and the mix ticket truck volume known, pump stroke volumes agreed more strongly with truck volumes during production pile installation.

- While AFF back-calculation was shown in some instances to produce stronger agreement between estimated and measured pile dimensions at the cut-off elevation, in general this approach is not practical. A number of uncertainties in the grout volume accounting process (auger re-strokes, volume accounting disagreement, among others) can lead to unreasonable AFF values. It is therefore recommended that the inspector visually estimate and record AFF at the point of grout return in the region of the auger above the ground surface yet below the drill rig scrapper. AFF estimations to the nearest 0.25 (e.g., 0.25, 0.5, 0.75, 1.0) will produce an acceptably accurate final pile volume.

- A booklet of common auger sizes and associated AFFs is recommended for auger cast pile installation. Auger models can easily be adjusted for uncommon or job specific auger configurations.

- If the AFF is not recorded or unknown during the post-construction integrity evaluation and final pile volume calculation, the full range of possible AFF values ($0.13 \leq AFF \leq 1.0$) should be assessed to define the best- and worst-case pile sizes. Therein, the use of an empty auger fill factor (AFF=0.13) is the most conservative approach for estimating as-built pile size. This results in the lowest possible contribution of volume 4 and the smallest possible pile size prediction. It should also be noted that the potential for pile size estimation error increases with increased return depth.

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Appendix A – Bridge 4 Data Collection Summary

Table A1. Bridge 4 Pier 1 Data Collection Summary

Bridge 4 Pier 1				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1				X
2				X
3				X
4				X
5				X
6				X
7				X
8				X
9				X
10				X
11				X
12				X

Table A2. Bridge 4 Pier 2R Data Collection Summary

Bridge 4 Pier 2R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X			
2	X			
3	X			
4	X			
5	X			
6	X			
7	X			
8	X			

Table A3. Bridge 4 Pier 3 Data Collection Summary

Bridge 4 Pier 3				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1		X	X	X
2		X	X	X
3		X	X	X
4		X	X	X
5		X	X	X
6		X	X	X
7		X	X	X
8		X	X	X
9		X	X	X
10		X	X	X
11		X	X	X
12		X	X	X
13		X	X	X

Bridge 4 Pier 3				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
14		X	X	X
15		X	X	X
16		X	X	X

Table A4. Bridge 4 Pier 4L Data Collection Summary

Bridge 4 Pier 4L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	X
3	X	X	X	X
4	X			X
5	X			X
6	X	X	X	X
7	X	X	X	X
8	X	X	X	X

Table A5. Bridge 4 Pier 4R Data Collection Summary

Bridge 4 Pier 4R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X			X
3	X			X
4	X	X	X	X
5	X	X	X	X
6	X			X
7	X			X
8	X			X
4R		X	X	

Table A6. Bridge 4 Pier 5 Data Collection Summary

Bridge 4 Pier 5				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X			
6	X	X	X	
7	X	X	X	
8	X	X	X	
9	X	X	X	

Table A7. Bridge 4 Pier 6 Data Collection Summary

Bridge 4 Pier 6				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X			
2	X			
3	X			
4	X			
5	X			
6	X			
7	X			
8	X			
9	X			
10	X			
11	X			
12	X			

Table A8. Bridge 4 Pier 7 Data Collection Summary

Bridge 4 Pier 7				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X			
2	X			
3	X			
4	X			
5	X			
6	X			
7	X			
8	X			

Table A9. Bridge 4 Pier 8 Data Collection Summary

Bridge 4 Pier 8				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
3				

Table A10. Bridge 4 Pier 14 Data Collection Summary

Bridge 4 Pier 14				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
2			X	
4			X	
5		X	X	
6		X	X	

Table A11. Bridge 4 Pier 15 Data Collection Summary

Bridge 4 Pier 15				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X		X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	

Table A12. Bridge 4 Pier 16 Data Collection Summary

Bridge 4 Pier 16				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	

Appendix B – Bridge 5 Data Collection Summary

Table B1. Bridge 5 Pier 11L Data Collection Summary

Bridge 5 Pier 11L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	X
3	X	X	X	X
4	X	X	X	X
5	X	X	X	X
6	X	X	X	X
7	X	X	X	X
8	X	X	X	X

Table B2. Bridge 5 Pier 12L Data Collection Summary

Bridge 5 Pier 12L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
2		X		

Table B3. Bridge 5 Pier 15L Data Collection Summary

Bridge 5 Pier 15L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	

Table B4. Bridge 5 Pier 15R Data Collection Summary

Bridge 5 Pier 15R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X		X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	

Table B5. Bridge 5 Pier 16L Data Collection Summary

Bridge 5 Pier 16L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	

Table B6. Bridge 5 Pier 16R Data Collection Summary

Bridge 5 Pier 16R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	

Appendix C – Bridge 7 Data Collection Summary

Table C1. Bridge 7 Pier 1 Data Collection Summary

Bridge 7 Pier 1				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	X
3	X	X	X	X
4	X	X	X	X
5	X	X	X	X
6	X	X	X	X
7	X	X	X	X
8	X	X	X	X
9	X	X	X	X

Table C2. Bridge 7 Pier 2L Data Collection Summary

Bridge 7 Pier 2L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	

Table C3. Bridge 7 Pier 2R Data Collection Summary

Bridge 7 Pier 2R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	

Table C4. Bridge 7 Pier 3 Data Collection Summary

Bridge 7 Pier 3				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X			
3	X	X	X	

Bridge 7 Pier 3				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X		X	
9	X	X	X	
10	X	X	X	
11	X	X	X	
12	X	X	X	
13	X	X	X	
14	X	X	X	
15	X	X	X	
16	X	X	X	

Table C5. Bridge 7 Pier 4L Data Collection Summary

Bridge 7 Pier 4L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	

Table C6. Bridge 7 Pier 4R Data Collection Summary

Bridge 7 Pier 4R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	

Table C7. Bridge 7 Pier 5L Data Collection Summary

Bridge 7 Pier 5L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	

Bridge 7 Pier 5L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	

Table C8. Bridge 7 Pier 5R Data Collection Summary

Bridge 7 Pier 5R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1		X	X	
2		X	X	
3		X	X	
4		X	X	
5		X	X	
6		X	X	
7		X	X	
8		X	X	

Table C9. Bridge 7 Pier 6L Data Collection Summary

Bridge 7 Pier 6L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	

Table C10. Bridge 7 Pier 6R Data Collection Summary

Bridge 7 Pier 6R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	

Table C11. Bridge 7 Pier 7 Data Collection Summary

Bridge 7 Pier 7				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	

Bridge 7 Pier 7				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	
9	X	X	X	
10	X	X	X	
11	X	X	X	
12	X	X	X	
13	X	X	X	
14	X	X	X	
15	X	X	X	
16	X	X	X	

Table C12. Bridge 7 Pier 8L Data Collection Summary

Bridge 7 Pier 8L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1		X	X	X
2		X	X	X
3		X	X	X
4		X	X	X
5		X	X	X
6		X	X	X
7		X	X	X
8		X	X	X

Table C13. Bridge 7 Pier 8R Data Collection Summary

Bridge 7 Pier 8R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1		X	X	X
2		X	X	X
3		X	X	X
4		X	X	X
5		X	X	X
6		X	X	X
7		X	X	X
8		X	X	X

Table C14. Bridge 7 Pier 9L Data Collection Summary

Bridge 7 Pier 9L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	X
3	X	X	X	X
4	X	X	X	X
5	X	X	X	X
6	X	X	X	X
7	X	X	X	X
8	X	X	X	X
9	X	X	X	X

Table C15. Bridge 7 Pier 9R Data Collection Summary

Bridge 7 Pier 9R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1		X	X	X
2		X	X	X
3		X	X	X
4		X	X	X
5		X	X	X
6		X	X	X
7		X	X	X
8		X	X	X
C				X
4A				X

Table C16. Bridge 7 Pier 10L Data Collection Summary

Bridge 7 Pier 10L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	

Table C17. Bridge 7 Pier 10R Data Collection Summary

Bridge 7 Pier 10R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	

Bridge 7 Pier 10R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
6	X	X	X	
7	X	X	X	
8	X	X	X	

Table C18. Bridge 7 Pier 11R Data Collection Summary

Bridge 7 Pier 11R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	X
3	X	X	X	X
4	X	X	X	X
5	X	X	X	X
6	X	X	X	X
8	X	X	X	X
9	X	X	X	X
10	X	X	X	X
4R		X		
4RR		X		
7RR	X	X	X	

Appendix D – Bridge 8 Data Collection Summary

Table D1. Bridge 8 Pier 1 Data Collection Summary

Bridge 8 Pier 1				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X		X	
2	X		X	
3	X		X	
4	X		X	
5	X		X	
6	X		X	
7	X		X	
8	X		X	
9	X		X	
10	X		X	
11	X		X	
12	X		X	
13	X			
14	X		X	
15	X		X	

Table D2. Bridge 8 Arch 1 Data Collection Summary

Bridge 8 Arch 1				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X			
3	X	X	X	
4	X	X	X	
5	X	X		
6	X	X	X	
7	X	X	X	
8	X	X	X	
9	X	X	X	
10	X	X	X	
11	X			
12	X	X	X	
13	X	X	X	
14	X	X		
15	X			
16	X	X	X	
17	X	X	X	
18	X	X	X	
19	X	X	X	
20	X	X	X	
21	X	X	X	
22	X	X	X	

Bridge 8 Arch 1				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
23	X	X	X	
24		X	X	
25	X	X	X	
26	X	X	X	
27		X		
28	X	X	X	
29	X	X	X	
30	X	X	X	
31	X	X	X	
32	X	X	X	
33		X		
34	X	X	X	
35	X	X	X	
36	X	X	X	
37	X	X	X	
38		X	X	
39		X	X	
40	X	X	X	
41	X	X	X	
42		X	X	

Table D3. Bridge 8 Arch 2 Data Collection Summary

Bridge 8 Arch 2				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	
9		X	X	
10	X	X	X	
11	X	X	X	
12	X	X	X	
13	X	X	X	
14	X			
15	X	X	X	
16	X	X	X	
17	X	X	X	
18	X	X	X	
19	X	X	X	
20	X	X	X	

Bridge 8 Arch 2				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
21	X	X	X	
22	X	X	X	
23	X	X	X	
24	X	X	X	
R9	X			

Table D4. Bridge 8 Arch 4 Data Collection Summary

Bridge 8 Arch 4				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5		X	X	
6	X	X	X	
7	X	X	X	
8	X			
9	X	X	X	
10	X	X	X	
11	X	X	X	
12	X			
13	X	X	X	
14	X	X	X	
15	X	X	X	
16		X	X	
17	X	X	X	
18	X	X	X	
19	X	X	X	
20	X	X	X	
21	X	X	X	
22	X	X	X	
23	X	X	X	
24	X			
25	X	X	X	
26	X	X	X	
27	X	X	X	
28	X	X	X	
29	X	X	X	
30	X	X	X	
31	X	X	X	
32	X	X	X	
33	X	X	X	
34	X	X	X	
35	X	X	X	

Bridge 8 Arch 4				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
36	X	X	X	
37	X	X	X	
38	X	X	X	
39	X	X	X	
40	X	X	X	
41	X	X	X	
42	X	X	X	
43	X	X	X	
44	X	X	X	
45	X	X	X	
46	X	X	X	
47	X	X	X	
48	X	X	X	
49	X	X	X	
50	X	X	X	
51	X	X	X	
52	X	X	X	
53	X	X	X	
54	X	X	X	
55	X	X	X	
56	X	X	X	
57	X	X	X	
58	X	X	X	
59	X	X	X	
60	X	X	X	
61	X	X	X	
62	X	X	X	
63	X	X	X	
64	X	X	X	
65	X	X	X	
66	X	X	X	
67	X	X	X	
68	X	X	X	
69	X	X	X	
70	X	X	X	
71	X	X	X	
72	X	X	X	
73	X	X	X	
74	X	X	X	
75	X	X	X	
76	X	X	X	
77	X	X	X	

Table D5. Bridge 8 Arch 5 Data Collection Summary

Bridge 8 Arch 5				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2		X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	
9	X	X	X	
10	X	X	X	
11	X	X	X	
12	X	X	X	
13		X	X	
14	X	X	X	
15	X	X	X	
16	X	X	X	
17	X	X	X	
18	X	X	X	
19	X	X	X	
20	X	X	X	
21	X	X	X	
22	X	X	X	
23	X	X	X	
24		X	X	
25	X	X	X	
26	X	X	X	
27	X	X	X	
28	X	X	X	
29	X	X	X	
30	X	X	X	
31	X	X	X	
32	X	X	X	
33	X	X	X	
34	X	X	X	
35	X	X	X	
36	X	X	X	
37	X	X	X	
38	X	X	X	
39	X	X	X	
40	X	X	X	
41	X	X	X	
42	X	X	X	
43	X	X	X	

Bridge 8 Arch 5				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
44	X	X	X	
45	X	X	X	
46		X	X	
47	X	X	X	
48	X	X	X	
49	X	X	X	
50	X	X	X	
51	X	X	X	
52	X	X	X	
53	X	X	X	
54	X	X	X	

Table D6. Bridge 8 Center Pier Data Collection Summary

Bridge 8 Center Pier				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	X
3	X	X	X	X
4	X	X	X	X
5	X	X	X	X
6	X	X	X	X
7	X	X	X	X
8	X	X	X	X
9	X	X	X	X
10	X	X	X	X
11	X	X		X
12	X	X	X	X
13	X	X	X	X
14	X	X	X	X
15	X	X	X	X
16	X	X	X	X
17	X	X	X	X
18	X	X	X	X
19	X	X	X	X
20	X	X	X	X
21	X	X	X	X
22	X		X	X
23	X	X	X	X
24	X	X	X	X
25	X	X	X	X
26	X	X	X	X
27	X	X	X	X
28	X		X	
29	X	X	X	X

Bridge 8 Center Pier				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
30	X	X	X	X
31	X	X	X	X
32	X	X	X	X
33	X	X	X	X
34	X	X	X	X
35	X	X	X	X
36	X	X	X	X
37	X	X	X	X
38	X	X	X	X
39	X	X	X	X
40	X	X	X	X
41	X	X	X	X
42		X	X	X
43		X	X	X
44		X	X	X
45	X	X	X	X
46	X	X	X	X
47	X	X	X	X
48	X	X	X	X
49	X	X	X	X
50	X	X	X	X
51	X	X	X	X
52	X	X	X	X
53	X	X	X	X
54	X	X	X	X
55	X	X	X	X
56	X	X	X	X
57	X	X	X	X
58	X	X	X	X
59	X	X	X	X
60	X	X	X	X
61	X	X	X	X
62	X	X	X	X
63	X	X	X	X
64	X	X	X	X
65	X	X	X	X
66	X	X	X	X
67	X	X	X	X
68	X	X	X	X
69	X	X	X	X
70	X	X	X	X
71	X	X	X	X
72	X	X		X
73	X	X	X	X

Bridge 8 Center Pier				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
74	X	X	X	X
75	X	X	X	X
76	X	X	X	X
77	X	X	X	X
78	X	X	X	X
79	X	X	X	X
80	X	X	X	X
81	X	X	X	X
82	X	X	X	X
83	X	X	X	X
84	X	X	X	X
85	X	X	X	X
86	X	X	X	X
87	X	X	X	X
88	X	X	X	X
89	X	X	X	X
90	X	X	X	X
91	X	X	X	X
92	X	X	X	X
93	X	X	X	X
94	X	X	X	X
95	X	X	X	X
96	X	X	X	X
97	X	X	X	X
98	X	X	X	X
99	X	X	X	X
100	X	X	X	X
101	X	X	X	X
102	X	X	X	X
103	X	X	X	X
104	X	X	X	X
105	X	X	X	X
106	X	X	X	X
107	X	X	X	X
108	X	X	X	X
109	X	X	X	X
110	X	X	X	X
111	X	X	X	X
112	X	X	X	X
113	X	X	X	X
114	X	X	X	X
115	X	X	X	X
116	X	X	X	X
117	X	X	X	X

Bridge 8 Center Pier				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
118	X	X	X	X
119	X	X	X	X
120	X	X	X	X
121	X	X	X	X
122	X	X	X	X
123	X	X	X	X
124	X	X	X	X
125	X	X	X	X
126	X	X	X	X
127	X	X	X	X
128	X	X	X	X

Table D7. Bridge 8 End Bent (EB) 2 Data Collection Summary

Bridge 8 EB2				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1		X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	
9		X	X	
10	X	X	X	
11	X	X	X	
12	X	X	X	
13	X	X	X	
14	X	X	X	
15		X	X	
16	X	X	X	
17		X	X	
18	X	X	X	

Table D8. Bridge 8 Arch 4 Data Collection Summary

Bridge 8 Arch 4				
Pile Number	TIP Data/Report	AME Data	Installation Logs	As-built Dimensions
1				X
2				X
3				X
4				X
5				X
6				X
7				X

Bridge 8 Arch 4				
8				X
9				X
10				X
11				X
12				X
13				X
14				X
15				X
16				X
17				X
18				X
19				X
20				X
21				X
22				X
23				X
24				X
25				X
26				X
27				X
28				X
29				X
30				X
31				X
32				X
33				X
34				X
35				X
36				X
37				X
38				X
39				X
40				X
41				X
42				X
43				X
44				X
45				X
46				X
47				X
48				X
49				X
50				X
51				X
52				X

Bridge 8 Arch 4				
53				X
54				X
55				X
56				X
57				X
58				X
59				X
60				X
61				X
62				X
63				X
64				X
65				X
66				X
67				X
68				X
69				X
70				X
71				X
72				X
73				X
74				X
75				X
76				X
77				X

Appendix E – Bridge 11 Data Collection Summary

Table E1. Bridge 11 Pier 2 Data Collection Summary

Bridge 11 Pier 2				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	

Table E2. Bridge 11 Pier 3 Data Collection Summary

Bridge 11 Pier 3				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X			
2	X			
3	X			
4	X			
5	X			
6	X			
7	X			
8	X			
9	X			
10	X			
11	X			
12	X			

Appendix F – Bridge 101 Data Collection Summary

Table F1. Bridge 101 Pier 1 Data Collection Summary

Bridge 101 Pier 1				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X			
2	X	X	X	
3	X			
4	X	X	X	
5	X			
6		X	X	
7	X			

Table F2. Bridge 101 Pier 2 Data Collection Summary

Bridge 101 Pier 2				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X			
3	X	X	X	
4	X			
5	X	X	X	
6	X	X	X	
7	X			
8	X	X	X	
9	X			
10	X	X	X	

Table F3. Bridge 101 Pier 3 Data Collection Summary

Bridge 101 Pier 3				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	X
3	X	X	X	X
4	X	X	X	X
5	X	X	X	X
6	X	X	X	X
7	X	X	X	
8	X	X	X	X
9	X	X	X	X
10	X	X	X	X
3-1	X	X	X	X
8-1	X	X	X	X

Table F4. Bridge 101 Pier 4 Data Collection Summary

Bridge 101 Pier 4				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X			
5	X	X	X	
6	X	X	X	
7	X			
8	X	X	X	
9	X			
10	X	X	X	

Table F5. Bridge 101 Pier 5 Data Collection Summary

Bridge 101 Pier 5				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X			
2	X			
3	X	X	X	
4	X			
5	X			
6	X	X	X	
7	X			
8	X			
9	X			
10	X	X	X	

Table F6. Bridge 101 Pier 6 Data Collection Summary

Bridge 101 Pier 6				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	X
3	X	X	X	X
4	X	X	X	X
5	X	X	X	X
6	X	X	X	X
7	X	X	X	X
8	X	X	X	X
9	X	X	X	X
10	X	X	X	X
11	X	X	X	X
12	X	X	X	X

Table F7. Bridge 101 Pier 7 Data Collection Summary

Bridge 101 Pier 7				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	
3	X	X	X	X
4	X	X	X	
5	X	X	X	X
6	X	X	X	X
7	X	X	X	X
8	X	X	X	
9	X	X	X	X
10	X	X	X	X
11	X	X	X	X
12	X	X	X	X
13				X
14				X
15				X

Table F8. Bridge 101 Pier 8 Data Collection Summary

Bridge 101 Pier 8				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	
9	X	X	X	
10	X	X	X	
11	X	X	X	
12	X	X	X	
13	X	X	X	
14	X	X	X	
15	X	X	X	

Table F9. Bridge 101 Pier 9 Data Collection Summary

Bridge 101 Pier 9				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	X
3	X	X	X	X
4	X	X	X	X
5	X	X	X	X

Bridge 101 Pier 9				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
6	X	X	X	X
7	X	X	X	X
8	X	X	X	X
9	X	X	X	X
10	X	X	X	X
11	X	X	X	X
12	X	X	X	X
13	X	X	X	X
14	X	X	X	X
15	X	X	X	X
3R		X	X	

Table F10. Bridge 101 Pier 10 Data Collection Summary

Bridge 101 Pier 10				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	
9	X	X	X	
10	X	X	X	
11	X	X	X	
12	X	X	X	
5R		X	X	

Table F11. Bridge 101 Pier 11 Data Collection Summary

Bridge 101 Pier 11				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1				X
2				X
3		X	X	X
4		X	X	
5		X	X	X
6				X
7				X
8		X	X	
9		X	X	X
10				X
11				X
12				X

Bridge 101 Pier 11				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
13				X
14				X
8R		X	X	
10R		X	X	

Table F12. Bridge 101 Pier 12 Data Collection Summary

Bridge 101 Pier 12				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1		X	X	
2		X	X	
3		X	X	
4		X	X	
5		X	X	
6		X	X	
8		X	X	
9		X	X	
11		X	X	
12		X	X	
13		X	X	
14		X	X	
15		X	X	

Table F13. Bridge 101 Pier 13 Data Collection Summary

Bridge 101 Pier 13				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	
9	X	X	X	
10	X	X	X	
11	X	X	X	
12	X	X	X	

Table F14. Bridge 101 Pier 16 Data Collection Summary

Bridge 101 Pier 16				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
4		X	X	
5		X	X	
10		X	X	

Bridge 101 Pier 16				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
11		X	X	

Table F15. Bridge 101 Pier 17 Data Collection Summary

Bridge 101 Pier 17				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X			X
2	X	X	X	X
3	X	X	X	X
4	X	X	X	X
5	X			X
6	X	X	X	X
7	X	X	X	X
8	X	X	X	X
9	X	X	X	X
10	X	X	X	X

Table F16. Bridge 101 Pier 18 Data Collection Summary

Bridge 101 Pier 18				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X			
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X			
9	X	X	X	
10	X	X	X	
11	X	X	X	
12	X	X	X	

Table F17. Bridge 101 Pier 19 Data Collection Summary

Bridge 101 Pier 19				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	X
3	X	X	X	X
4	X	X	X	X
5		X	X	
6	X	X	X	X
7	X	X	X	X
8	X	X	X	X

Bridge 101 Pier 19				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
9	X	X	X	X
10	X	X	X	X
11	X			X
12	X	X	X	X

Table F18. Bridge 101 Pier 20 Data Collection Summary

Bridge 101 Pier 20				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X		X	
6	X	X	X	
7	X	X	X	
8	X	X	X	
9	X	X	X	
10	X	X	X	

Table F19. Bridge 101 Pier 21 Data Collection Summary

Bridge 101 Pier 21				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	
9	X	X	X	
10	X	X	X	
11	X	X	X	
12	X	X	X	

Table F20. Bridge 101 Pier 22 Data Collection Summary

Bridge 101 Pier 22				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	X
3	X	X	X	X
4	X	X	X	X
5	X	X	X	X

Bridge 101 Pier 22				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
6	X	X	X	X
7	X	X	X	X
8	X	X	X	X
9	X	X	X	X
10	X	X	X	X
11	X	X	X	X
12	X	X	X	X

Table F22. Bridge 101 Pier 23 Data Collection Summary

Bridge 101 Pier 23				
Pile Number	TIP Data/Report	AME Data	Installation Logs	As-built Dimensions
1				
2				
3		X	X	
4				
5				
6				
7				
8		X	X	

Table F23. Bridge 101 Pier 24 Data Collection Summary

Bridge 101 Pier 24				
Pile Number	TIP Data/Report	AME Data	Installation Logs	As-built Dimensions
1		X	X	
2		X	X	
3		X	X	
4		X	X	
5		X	X	
6		X	X	
7		X	X	
8		X	X	
9		X	X	
10		X	X	
11		X	X	
12		X	X	

Table F24. Bridge 101 Pier 25 Data Collection Summary

Bridge 101 Pier 25				
Pile Number	TIP Data/Report	AME Data	Installation Logs	As-built Dimensions
1				
2				
3				
4		X	X	

Bridge 101 Pier 25				
5		X	X	
6		X	X	
7				
8		X	X	
9				
10		X	X	
11		X	X	
12		X	X	

Table F25. Bridge 101 Pier 26 Data Collection Summary

Bridge 101 Pier 26				
Pile Number	TIP Data/Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X			
8	X	X	X	
9	X			
10	X	X	X	
11	X	X	X	
12	X	X	X	

Table F26. Bridge 101 Pier 26 Data Collection Summary

Bridge 101 Pier 26				
Pile Number	TIP Data/Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	

Table F27. Bridge 101 Pier 27 Data Collection Summary

Bridge 101 Pier 27				
Pile Number	TIP Data/Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	

Bridge 101 Pier 27				
8	X	X	X	
9	X	X	X	
10	X	X	X	
11	X	X	X	
12	X	X	X	

Table F28. Bridge 101 Pier 28 Data Collection Summary

Bridge 101 Pier 28				
Pile Number	TIP Data/Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	
9	X	X	X	
10	X	X	X	
11	X	X	X	
12	X	X	X	

Table F29. Bridge 101 Pier 29 Data Collection Summary

Bridge 101 Pier 29				
Pile Number	TIP Data/Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	
9	X	X	X	
10	X	X	X	
11	X	X	X	
12	X	X	X	

Table F30. Bridge 101 Pier 30 Data Collection Summary

Bridge 101 Pier 30				
Pile Number	TIP Data/Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	

Bridge 101 Pier 30				
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	
9	X	X	X	
10		X	X	
11	X	X	X	
12	X	X	X	

Table F31. Bridge 101 Pier 35 Data Collection Summary

Bridge 101 Pier 35				
Pile Number	TIP Data/Report	AME Data	Installation Logs	As-built Dimensions
1	X		X	
2	X		X	
3	X		X	
4	X		X	
5	X		X	
6	X		X	
7	X		X	
8	X		X	
9	X		X	
10	X		X	
11	X		X	
12	X		X	

Table F32. Bridge 101 Pier 36 Data Collection Summary

Bridge 101 Pier 36				
Pile Number	TIP Data/Report	AME Data	Installation Logs	As-built Dimensions
1	X		X	
2	X		X	
3	X		X	
4	X		X	
5	X		X	
6	X		X	
7	X		X	
8			X	
9	X		X	
10	X		X	
11	X		X	
12			X	
13	X		X	
14	X		X	

Appendix G – Bridge 102 Data Collection Summary

Table G1. Bridge 102 Pier 2 Data Collection Summary

Bridge 102 Pier 2				
Pile Number	TIP Data/Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X		X	
3	X		X	
4	X		X	
5	X	X	X	
6	X		X	
7	X		X	
8	X		X	
9	X	X	X	
10	X		X	
11	X		X	
12	X		X	
13	X	X	X	
14	X		X	
15	X		X	
16	X		X	

Table G2. Bridge 102 Pier 3R Data Collection Summary

Bridge 102 Pier 3R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
7	X			
8	X			
9	X			
10	X			
11	X			
12	X			

Table G3. Bridge 102 Pier 4L Data Collection Summary

Bridge 102 Pier 4L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X		
7	X	X	X	
8	X	X	X	

Table G4. Bridge 102 Pier 4R Data Collection Summary

Bridge 102 Pier 4R

Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
9	X			
10	X			
11	X			
12	X			
13	X			
14	X			

Table G5. Bridge 102 Pier 5L Data Collection Summary

Bridge 102 Pier 5L				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	

Table G6. Bridge 102 Pier 5R Data Collection Summary

Bridge 102 Pier 5R				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
9		X	X	
10		X	X	
11		X	X	
12		X	X	

Table G7. Bridge 102 Pier 6 Data Collection Summary

Bridge 102 Pier 6				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	X
3	X	X	X	X
4	X	X	X	X
5	X	X	X	X
6	X	X	X	X
7	X	X	X	X
8	X	X	X	X

Table G8. Bridge 102 Pier 9 Data Collection Summary

Bridge 102 Pier 9				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1				
2	X	X	X	

3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	
9	X	X	X	

Table G9. Bridge 102 Pier 10 Data Collection Summary

Bridge 102 Pier 10				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	X
3	X	X	X	X
4	X	X	X	X
5	X	X	X	X
6	X	X	X	X
7	X			X
8	X	X	X	X
9	X	X	X	X

Table G10. Bridge 102 Pier 11 Data Collection Summary

Bridge 102 Pier 11				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	X
2	X	X	X	X
3	X			
4	X	X	X	X
5	X	X	X	
6	X			
7	X	X	X	X
8				
9	X	X	X	X
10	X	X	X	X
11				X
12				X
13				X
14				X

Appendix H – Bridge 103 Data Collection Summary

Table H1. Bridge 103 Pier 5 Data Collection Summary

Bridge 103 Pier 5				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	

Table H2. Bridge 103 Pier 6 Data Collection Summary

Bridge 103 Pier 6				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X	X	X	
9	X	X	X	
10	X	X	X	

Table H3. Bridge 103 Pier 7 Data Collection Summary

Bridge 103 Pier 7				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1		X	X	
2		X	X	
3		X	X	
4		X	X	
5		X	X	
6		X	X	
7		X	X	
8		X	X	
9		X	X	
10		X	X	

Table H4. Bridge 103 Pier 8 Data Collection Summary

Bridge 103 Pier 8				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1		X	X	X
2		X	X	X
3		X	X	X
4		X	X	X
5		X	X	X
6		X	X	X
7		X	X	X
8		X	X	X
9		X	X	X
10		X	X	X

Appendix I – Bridge 104 Data Collection Summary

Table I1. Bridge 104 Pier 2 Data Collection Summary

Bridge 104 Pier 2				
Pile Number	TIP Data/ Report	AME Data	Installation Logs	As-built Dimensions
1	X	X	X	
2	X	X	X	
3	X	X	X	
4	X	X	X	
5	X	X	X	
6	X	X	X	
7	X	X	X	
8	X		X	