Frequency of Observed Anomalies in Drilled Piles Integrity Tested by Thermal Methods

Brent Robinson, Ph.D., P.E., M.ASCE[1]

[1] Pile Dynamics, Inc., 30725 Aurora Rd, Solon, OH 44139; e-mail: brobinson@pile.com

ABSTRACT

The structural integrity of concrete cast in place drilled foundations is often determined by cross hole sonic logging, low strain impact-echo, gamma-gamma logging or thermal integrity methods. Studies have characterized the frequency of observed significant anomalies detected by the first three methods. This study reviews a large database of drilled foundations tested by thermal methods over the last seven years. The frequency and general location in the shaft of major anomalies, as characterized by a 6% effective radius reduction criteria, are summarized and reviewed. Based on this criteria, anomalies occur in approximately 15% of the 2104 shafts reported. Of those 318 drilled foundations with anomalies, 77 (28%) identified anomalies occur within a length equivalent to the bottom two diameters of the foundation element, a rate similar to that reported by studies using other integrity methods.

INTRODUCTION

Concrete is placed in excavations for drilled foundations by continuous flight auger or tremie methods in either semi-inspectable dry holes or under bentonite, polymer or other drilling fluids. These techniques make inspection and quality assurance of the placed concrete difficult, at best. Initially, inspection was limited to visual inspection and tracking the number of trucks or volume of concrete placed in the hole. In the late 1960's, sonic echo or low strain integrity testing was introduced (as summarized in Hertlein and Davis, 2006). Low strain testing was used as a means of estimating the foundation element length and finding the depth to significant reductions in impedance, as characterized by area and material properties.

To address some limitations of low strain testing and other surface techniques, downhole test methods were introduced in the 1980's to provide profiles of the concrete inside the reinforcement cage. These include crosshole sonic logging and gamma-gamma testing (Hertlein and Davis, 2006). To estimate concrete cover thickness and to characterize soil intrusions and concrete issues outside the reinforcement cage, research in the early 2000's on thermal methods led to measurements by probes in access ducts and eventually embedded sensors at access locations (Mullins, 2010). Most of these methods have been standardized (ASTM D5882, ASTM D6760 and ASTM D7949), and are used worldwide for quality assurance of drilled foundations. Brown et al. (2016) provided a table of applications, limitations and advantages for common NDT methods applied to drilled foundations.

Thresholds to distinguish anomalies are popular among specifiers and owners, as they provide guidance on when integrity testing results may trigger further engineering review or on-site investigation. There is generally some debate that thresholds are either too strict (thereby hindering constructability) or too lenient (thereby potentially increasing risk to the overall performance of the structure). As an example, several thresholds have been suggested for CSL, with some entities identifying anomalies at a 20% or greater calculated wave speed delay (Jalinoos et al., 2005), while others define graduated categories based on first arrival time delays or energy, such as proposed by Webster et al. (2011) or Sellountou et al. (2019).

BACKGROUND

Several authors have investigated the frequency of anomalies for a variety of different integrity testing methods applied to drilled foundations. Amir and Amir (2008) reviewed data from 80,000 low strain integrity testing records. Based on comments appended to approximately 6000 records, they observed 1.85% noted a geometry change, defined as a neck, bulge, flaw or change in length. Separate analyses indicated 6% of these foundations were shorter than planned by 20 or more percent. That study did not indicate what criteria were applied for these interpretations or whether further interpretation of the data was submitted in more formal reports. O'Neill and Farhan (2004) reviewed early, predominantly gamma gamma logging data from 1996-2000 from the California Department of Transportation. Using the Department's thresholds that were applied at the time, nearly 20% of drilled shafts in their database had defined anomalies.

Cross hole sonic logging anomalies were reported by Faiella and Superbo (1998) on sites across Italy. Of 6800 drilled shafts tested on power plant and other electrical transmissions sites, between 10% and 40% of shafts tested had anomalies that triggered their threshold for further evaluation. Similar studies by Murrell (2013) and Jones and Wu (2005) further investigated the location of the anomalies along the shaft length and the frequency of anomalies, defined as Jalinoos et al. (2005). Jones and Wu (2005) indicated 38% of the shafts in their database had anomalies that met their threshold, with 45% in the bottom third of the shaft, 44% in the top third, and 11% in the middle.

Murrell (2013) reviewed 850 drilled shafts on 66 South Carolina projects, where more than half had fewer than eight shafts. They observed 14% of tested shafts had anomalies exceeding the 20% wave speed reduction threshold, with 32% in the bottom two diameters of the foundation element and 58% in the top two diameters of the foundation element. Most coring on the projects, particularly in cased upper sections indicated bleed water or minor segregation features that were not selected for further remediation.

A large scale study of the types described above has, to the author's knowledge, not been undertaken for integrity testing by thermal methods. Studies on a small number of drilled shafts with manufactured defects have been reported (recently Boeckmann and Loehr, 2019; Stark 2022; Boeckmann et al. 2021), as have field case histories (Hannigan and Moghaddam, 2019; Hyatt et al. 2019).

SUGGESTED THRESHOLD FOR THERMAL METHOD

Piscsalko et al. (2016) proposed an evaluation method based on structural loading conditions. Thermal integrity measurements are combined with placed concrete volume to estimate an effective radius versus depth. Effective radius is defined in this analysis as the radius of intact concrete that would exhibit the measured temperature at a depth. Reductions in temperature are then analogous to reductions in effective radius. The analyst can then identify reductions in effective radius that would yield reductions in structural resistance to load. The authors suggested a 6% effective radius reduction from the design radius, as this would have a greater than 20% reduction to moment of inertia. The method proposes labels of Satisfactory if the radius reduction is less than 6% and the minimum cover criteria are met, while identifying an Anomaly if the radius reduction is greater than 6% or the minimum cover criteria are not met.

The Piscsalko et al. (2016) criteria could be modified if required bending resistance is minimal on a project. A review of the loading cases could indicate an anomalous foundation element is acceptable based on the location and severity of the reduction. If the anomaly is in a portion of the shaft that is more critically loaded, then further evaluation by coring, load testing or alternate integrity tests can be performed. Like all non-destructive test methods, the results of any single integrity test should not be the sole basis for shaft acceptance or rejection.

METHODOLOGY

A sample of reports by GRL Engineers, Inc. that used the Piscsalko et al. (2016) criteria to identify foundation elements with potential anomalies was performed on projects tested from 2016 to 2023. These elements were tested in general accordance with ASTM D7949-2014. Access locations were either embedded sensors or access ducts for use with a thermal probe. The interpretations in the reports were performed by a number of different engineers on 238 construction projects, including infrastructure, commercial buildings and electrical transmission lines. The database was assembled by recording the diameter, length, thermal access locations, time to peak temperature, concrete volume placed, and the category based on the aforementioned criteria (Satisfactory or Anomalous). The approximate location of anomalies below the top of the foundation element was also recorded.

RESULTS AND DISCUSSION

The distribution of tested foundation element lengths, diameters, and number of thermal access locations is presented in Figure 1. The most common number of access locations are one and four, accounting in total for 57% of the elements tested. Foundations with one wire are placed on a central reinforcing bar when no cage is available, per ASTM D7949-14, which is typical of a variety of augered piles and micropiles. Four access locations are generally spaced equidistant around the reinforcement cage and used for elements of 1.2 m diameter or less, following the requirement in ASTM D7949 of one measurement location for every 0.3 m of the foundation element diameter (or one location per foot of diameter in Imperial units). Even numbers of thermal access locations are more common than odd, reflecting the preference of ASTM D7949 for even numbers of measurement locations. When spaced evenly, an even number of access locations are more symmetric, which in turn makes interpreting thermal data for cage shifting more straightforward. Most elements tested were up to 30 m long. The maximum length was 67 m.

Thermal measurements are interpreted for anomalies between casting and just past the peak measurement temperature at the access locations during concrete hydration (Belardo et al. 2021), with particular focus at the time of peak and a point in time halfway between peak temperature and the end of the pour. Figure 2 shows the time distribution for this data set, with the most common peak time between 10 and 20 hours after installation. In general, larger shafts peak later, while the exact time and magnitude of peak temperature is heavily influenced by the concrete mix design and added chemical admixtures, as modeled by Mullins (2010).

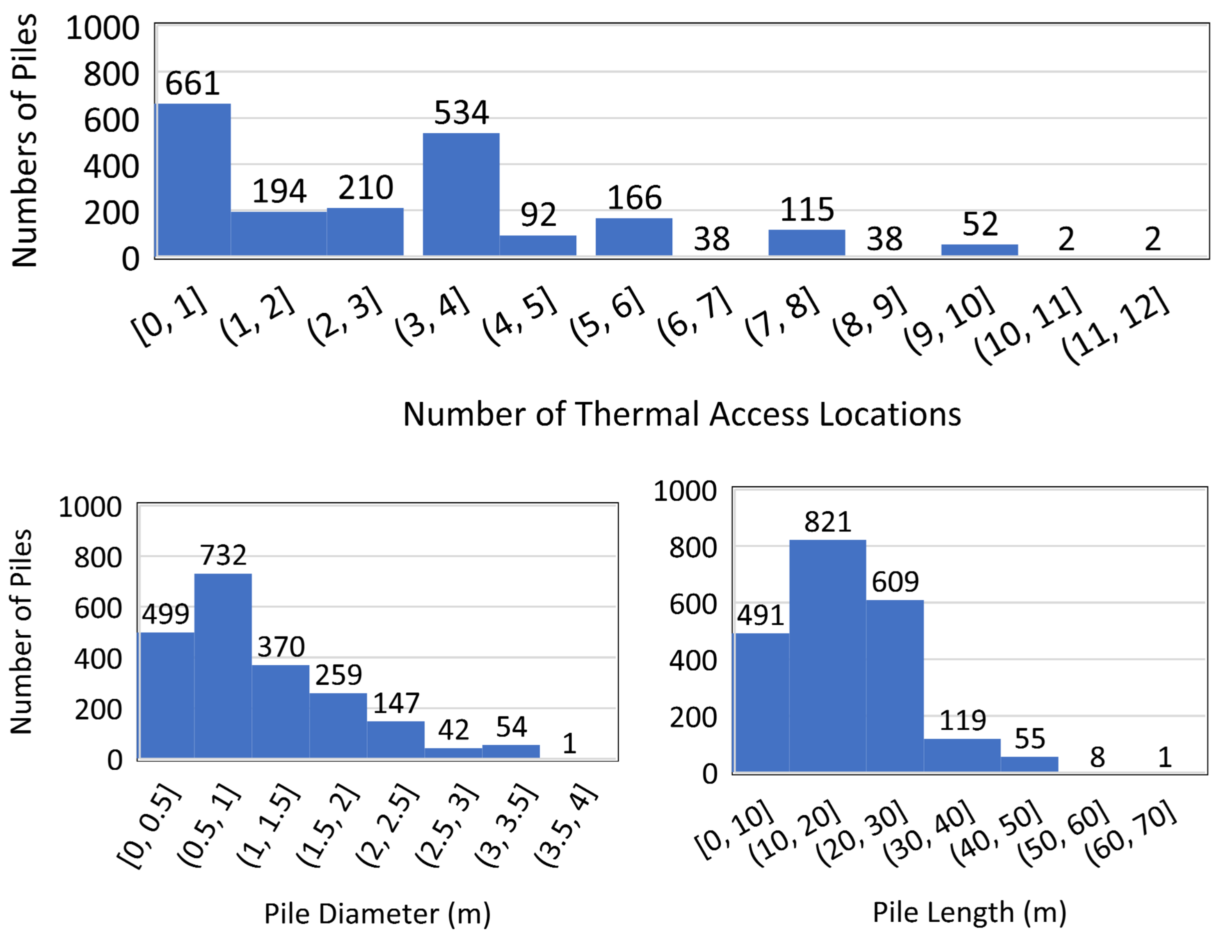

Figure 1. Distribution of Thermally Tested Foundation Elements by Access Locations, Diameter and Length.

Table 1 indicates the rate of thermal anomalies by the number of access locations. On the whole, an identified anomaly rate of 15% was observed. The prevalence of anomalies in single wire shafts was nearly the same as the overall average. A relatively small number of shafts with 7 and 9 access locations are included in the data set, and those shafts are on a relative handful of sites (10 and 5, respectively), which may skew the results and indicate more data is needed on these sizes. In general, this rate of anomalies is within the range of anomalies identified in earlier cited studies of cross hole sonic and gamma gamma logging.

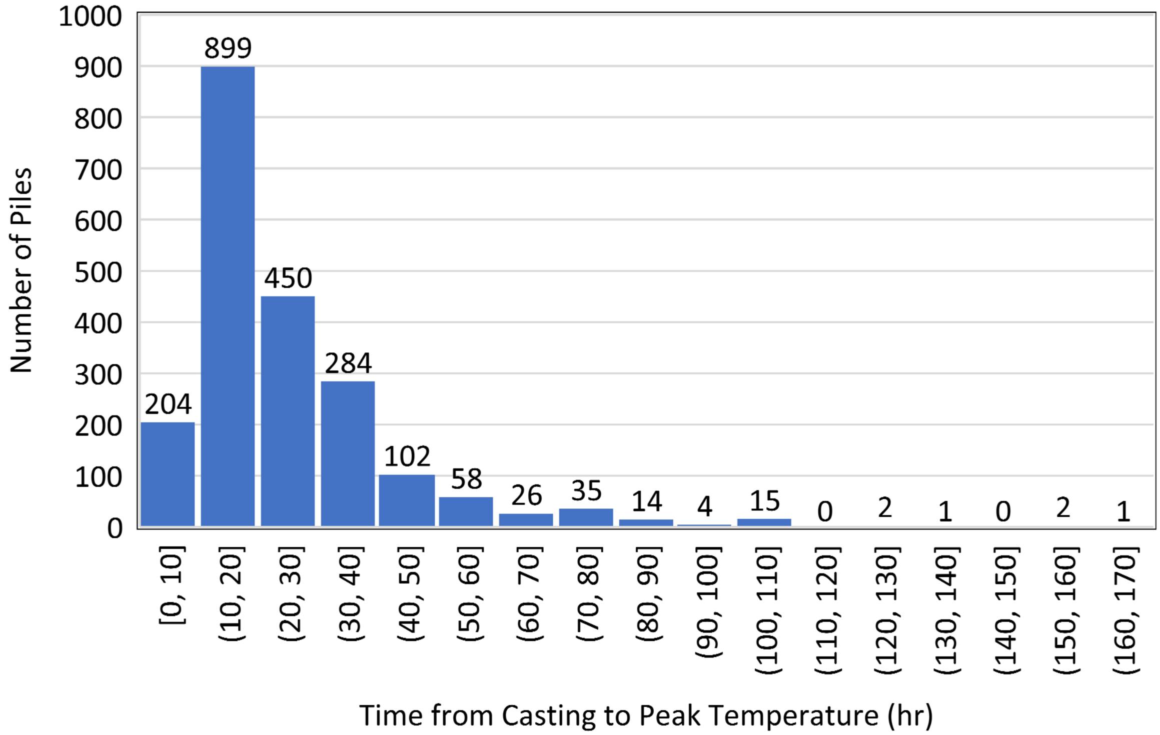

Figure 2. Distribution of Time from End of Casting to Peak Temperature at Access Locations.

Table 1. Anomaly Rate by Number of Access Locations.

Access Locations	**Diameter (m)**			**Total Number**	**Percent Satisfactory**	**Percent Anomaly**
	Minimum	**Median**	**Maximum**			
1	0.15	0.41	0.91	661	84	16
2	0.41	0.61	1.83*	194	84	16
3	0.41	0.91	1.22	210	82	18
4	0.61	1.07	1.98	534	85	15
5	1.37	1.52	2.13	92	89	11
6	1.37	1.83	2.13	166	84	16
7	1.68	2.13	2.44	38	97	3
8	1.98	2.44	2.74	115	93	7
9	2.44	2.74	3.05	38	92	8
>10	2.74	3.05	3.66	56	79	21
All	**0.15**	**0.91**	**3.66**	**2104**	**85**	**15**

***-** Two shafts of 1.83 m diameter were monitored. Removing these two outliers, the maximum was 0.91 m for two wire shafts.

A common concern expressed for thermal methods is the identification of soft bottom conditions, or conditions where a layer of sediment or mixed concrete, spoils and drilling fluid remain at the base of the foundation element (Brown et al. 2018). Figure 3 shows a dataset with a soft bottom as it is commonly observed. At this site, the 1 m diameter shaft was founded in soils with an average soil temperature at depth of approximately 28 degrees Celsius. The temperature below 29.5 m does not change, indicating the concrete is not curing. Even without adding the concrete volume, an analyst can identify a soft bottom condition in cases like these. An inclusion is also noted at 12 m near thermal access location 2.

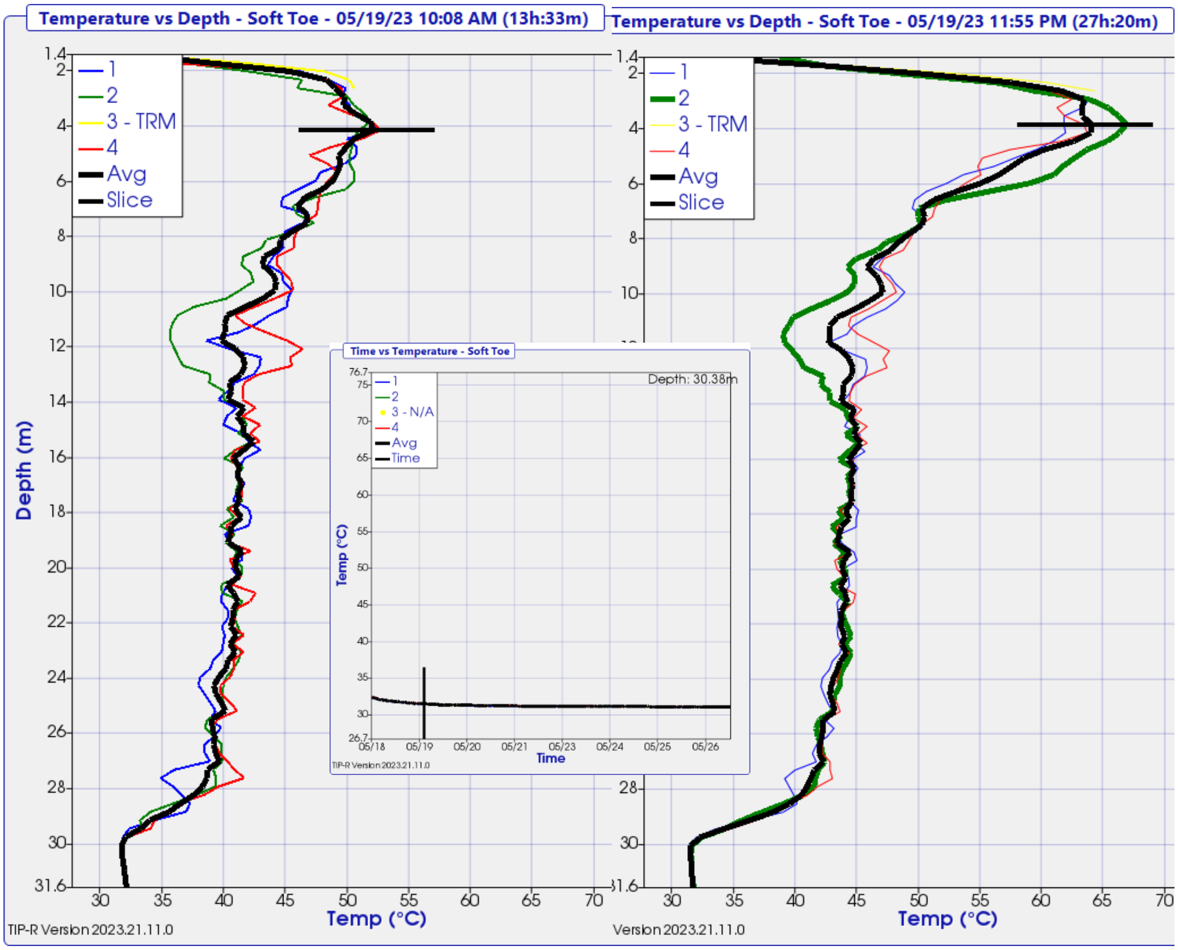

Figure 3. Thermal Profile of a 1 m diameter drilled shaft at times of halfway to peak (right) and peak (left). From 29.5 m to the bottom, no temperature gain is measured (inset), indicating a soft bottom.

The observed anomaly locations were grouped based on the methodology using top and bottom two diameters used in Murrell (2013) and dividing the length into thirds like Jones and Wu (2005). Figure 4 indicates the distributions for the thermal integrity dataset. Of the elements with anomalies in the bottom two diameters, 75% of those were within one diameter of the bottom. Comparing to the conclusions in Murrell (2013), where the bulk of the anomalies (58%) were identified in the top, the distributions in Figure 4 are likely a function of thermal methods being less affected by the thin bleed water channels prevalent in their CSL data. Debonding of access tubes is an issue that generates anomalies in CSL testing that also generally occurs from the top of the shaft down, and that influence would also not be present in thermal data.

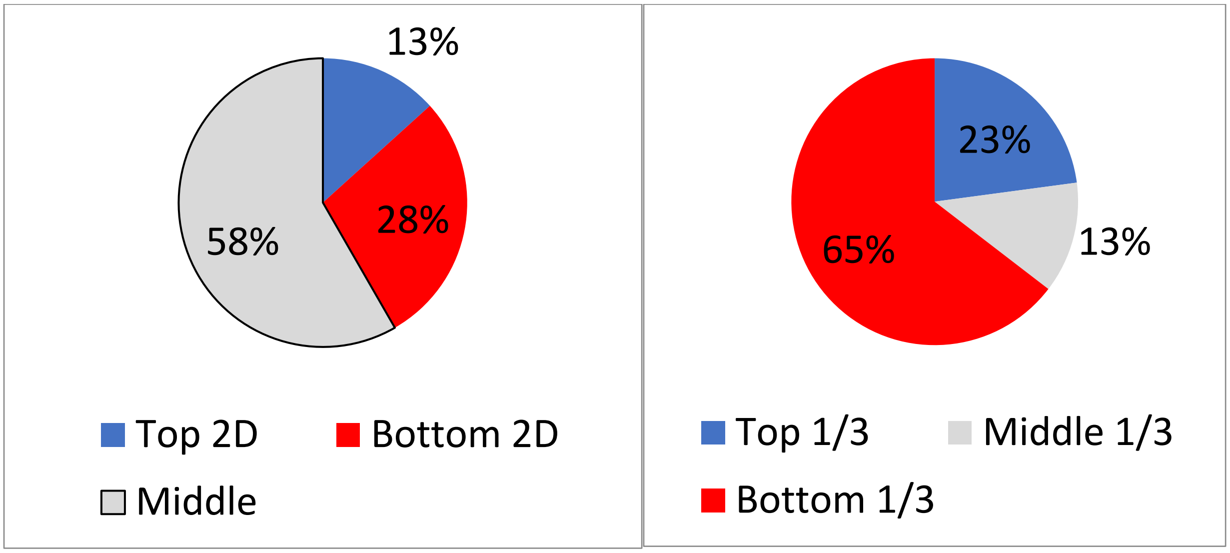

Figure 4. Distribution of anomaly locations along the shaft length for this study.

CONCLUSIONS

A dataset of report results from 2104 drilled foundation elements tested by multiple offices of GRL Engineers was compiled. The data reviewed the number of thermal access locations, the length and diameter of the foundation elements, the volume of concrete placed, the time for the concrete to reach a peak measured temperature and the presence of anomalies. Approximately 15% of the foundation elements tested were identified with anomalies based on the criteria established by Piscsalko et al. (2016), which combines concrete volumes from installation inspection with thermal measurement around the reinforcement cage versus depth. Single wire shafts on smaller diameter foundation elements had a similar rate of anomalies to the overall average. Of the shafts with anomalies, 28% had identified anomalies within two diameters of the bottom of the element, and 75% of those were within one diameter of the bottom. The total frequency and location of anomalies is consistent with other published studies on anomalies identified by cross-hole sonic logging, low strain integrity testing and gamma-gamma logging. Unfortunately, the reports did not include information about any coring, engineering analysis of the foundation element with potential reductions in radius or strength, or discussions with project engineers on site to determine what was done with these anomalous test results, as information would come well after report submittal.

As with any study of this nature, and, in particular with the simple application of a fixed threshold to non-destructive integrity testing data, the anomaly rate will be changed if the threshold is made more or less stringent. As discussed in Boeckmann et al. (2022), once such criteria are applied, the next step is to carefully review the drilled foundation element in light of the load bearing, serviceability, durability and other requirements identified by the design and project professionals involved. They can then decide whether further action or remediation of the shaft is required.

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