INTEGRITY ASSESSMENT OF A DIAPHRAGM WALL USING THERMAL INTEGRITY PROFILING

Sumanth H C, Sarathy Geotech and Engineering Services Pvt Ltd, Bengaluru, Karnataka, India, +91 9844875450, sumanth@sarathygeotech.com
Parthasarathy C R, Sarathy Geotech and Engineering Services Pvt Ltd, Bengaluru, Karnataka, India, +91 9844279055, partha@sarathygeotech.com
Brent Robinson, Pile Dynamics Inc., Cleveland, Ohio, USA, +1 (216) 831-6131, BRobinson@pile.com
Satish Y, Sarathy Geotech and Engineering Services Pvt Ltd, Bengaluru, Karnataka, India, +91 8660685489, satish@sarathygeotech.com
Sourav G, Sarathy Geotech and Engineering Services Pvt Ltd, Bengaluru, Karnataka, India, +91 8660960201, sourav@sarathygeotech.com

ABSTRACT

Assessing the integrity of sub-structures is imperative to ensure the effectiveness and sustainability of construction practices. Once sub-structures are erected, gathering information about their integrity becomes a challenging task. This study specifically focuses on evaluating the integrity of a diaphragm wall constructed in Bengaluru using thermal integrity profiling. The testing procedure involves the meticulous installation of thermal sensors along the reinforcement cage at one-foot intervals, covering the entire cage. Following the lowering of the cage, data acquisition devices are connected to each wire, enabling real-time data transmission to the cloud every 15 minutes during the concreting process, and facilitating remote monitoring. Data collection continues post-concreting until the peak temperature is reached. The obtained results are scrutinized for the panel's temperature profile consistency and alignment at the peak temperature. Panel integrity is assessed based on the average temperature measurements from each thermal wire at each depth increment. The data derived from this comprehensive test can unveil localized increases in concrete, indicative of bulges, as well as decreases in cross-sections. The study concludes by presenting the findings and insights from the thermal integrity test, accompanied by a detailed discussion on the merits and demerits of the testing methodology.

Keywords: Thermal Integrity Profiling, Thermal Sensors, Diaphragm Wall, Integrity, Cage Alignment.

INTRODUCTION

Diaphragm walls are reinforced concrete walls that are cast in-situ (on-site) using a deep trench excavation technique. These walls are typically constructed to provide lateral support and structural stability in situations where deep excavations are necessary, such as in underground structures like basements, tunnels, and deep foundations for buildings and bridges. They are an effective solution for providing temporary or permanent support in deep excavation projects, offering strength, stability, and versatility in challenging urban environments.

Pile foundations are employed when the soil at shallow depths is weaker or when the super structural loads are of higher order. Pile foundations bypass the weaker deposits at shallow depths and embed into the competent soil or rock mass to derive the capacity. The diameter and length of circular pile foundations are often huge and they are used to sustain higher super structural loads. In the recent times, pile foundation construction has been the new norm for infrastructural projects likes metros, bridges, high speed rails, and power projects. Circular pile foundations can be tested for integrity using a pile integrity test, cross-hole sonic logging test and high-strain dynamic test. Various limitations like accuracy of results, integrity of the cover region and cage alignment involving these methods have been appraised by the latest technology named thermal integrity profiling. The integrity of diaphragm walls and pile foundations needs to be ensured as these are built underground and inaccessible to physical inspection. Integrity is often pronounced concerning continuity, physical dimensions, and consistency of the material used in the construction.

Thermal Integrity Profiling known as TIP, assesses the integrity of the horizontal and vertical cross section of the deep foundation element. TIP provides information that can save future consequences with respect to the construction methodology and health of the structure.

THERMAL INTEGRITY PROFILING

A sophisticated non-destructive testing method called Thermal Integrity Profiling (TIP) is used to evaluate the structural integrity of deep foundation components such diaphragm walls, augured piles, drilled shafts, and other cast-in-place foundations. Finding internal irregularities that can jeopardize the foundation's strength and stability is one area in which it is especially helpful. The distribution of temperature from heat generated by curing concrete is the fundamental idea underlying TIP. Because cement hydrates, concrete has an exothermic reaction throughout the curing and setting process. The generation of heat in a well-constructed pile or shaft is relatively consistent with depth. TIP makes use of this thermal activity to find any possible flaws or irregularities in the foundation element.

The general procedure is as follows:

1. **Installation of thermal sensors**: TIP requires series of thermal sensors in multiple numbers embedded in the structure. The number of wires depends on the type of structure, geometry and structural features. These sensors are spaced vertically at one sensor per 300 mm.Wires are placed around the circumference of the shaft or pile at with one wire for every 300 mm of shaft diameter. The wires are installed before lowering of the reinforcement cage into the pile borehole or excavated space.
2. **Data Collection**: The data is collected through acquisition devices called thermal aggregators (TAG) and thermal acquisition ports (TAP). The wires are physically connected to these acquisition ports and can be uploaded to the cloud upon configuring the wires in each pile. The data collection commences once concreting operation begins. As the concrete cures, the sensors continuously measure the temperature at various locations within the element. This data is recorded and over several hours to days to capture the initial curing process until the peak temperature is achieved.
3. **Real-Time Availability of the data** : The thermal data is recorded and uploaded every 15 minutes to the configured cloud space. The data can be viewed real time every 15 minutes for real-time tracking and updating.
4. **Data Analysis:** Once the data collection period is complete, the temperature readings are analyzed to create a thermal profile of the foundation element as temperature versus depth. This profile reveals the distribution of heat generated by the curing concrete.
5. **Detection of Anomalies:** The thermal profile allows engineers to identify areas where the temperature deviates from the expected pattern, or an anomaly in the record. Lower temperatures might indicate voids, inclusions, cement loss, or inadequate concrete coverage, while higher temperatures might suggest an unusually high cement content or excess concrete volume. Comparing the temperature profile of individual wires along the vertical depth of the structure can also be a tool to identify the alignment of the cage.
6. **Assessment and Reporting:** After identifying any anomalies, engineers can assess the significance of these findings in the context of the available information, structure's design, and requirements. A report is then generated, detailing the results and recommending further action if needed.

   TIP offers several advantages in the construction and inspection of deep foundations. It provides detailed information about the distribution of temperatures in the structure, allowing for a thorough assessment of integrity and quality. TIP allows engineers to identify potential issues early in the construction process, reducing the risk of costly repairs or safety concerns later on. TIP does not require intrusive drilling or core sampling, preserving the integrity of the structure during testing. Comparisons between TIP, crosshole sonic logging (CSL), low strain integrity testing or coring in various drilled foundations can be found starting Mullins et al. (2005) and most recently in Boeckmann et al. (2022), Stark et al. (2022), Coleman and Belardo (2023), and White et al. (2023). A comparison of costs is outside the scope of this paper, but a framework and example for evaluating total project schedule and monetary costs of TIP and CSL are described by Hyatt et al. (2019).

DIAPHRAGM WALL

A set of diaphragm walls is scheduled to be installed along the periphery of the proposed 20-story residential building, as depicted in Fig 1. These walls are intended to serve as both protective boundaries and barriers against water seepage, given the proximity of a water body to the construction site.

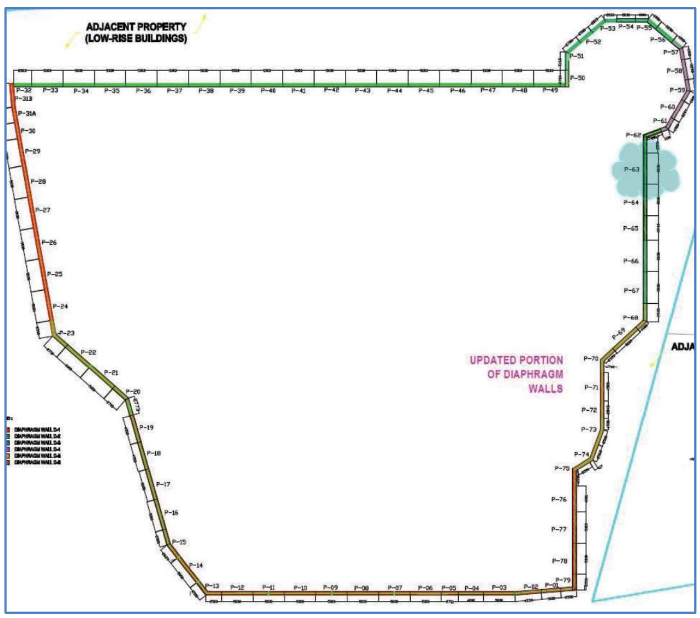


Fig 1. Layout of Diaphragm walls

Table 1. Diaphragm wall panel details

Panel Name	P-63
Type of Panel	Primary
Dimensions of the Panel, m	W*L1*L2 – 0.6*5*17.8
Design Cover, mm	75
Theoretical Concrete Volume, m^3	53.4
Actual Concrete Volume, m^3	59 (110.5%)
Cut-Off Level, m	+95.4
Toe Level, m	+77.6

Following several meetings and discussions with all stakeholders engaged in the current project, Panel-63 was selected for integrity testing through thermal integrity profiling for the diaphragm wall in Bengaluru. A total of 10 thermal wires were installed on the reinforcement cage of Panel-63. The specifics of the panel are outlined in Table 1. The geotechnical data at panel-63 location comprises of filled-up overburden from the top of the panel up to 6.5m followed by silty sand up to 12.5m. This is underlaid by cemented sand from 12.5m to 16.5m and rested in weathered rock strata from 16.5m to 17.8m. The diaphragm wall had 16 anchor points across four different levels, as illustrated in Fig 2. Each level contained four anchors, designed as enclosed void spaces that were sealed at both ends. These voids were intended to enable the installation of soil anchors after the soil was excavated on one side of the diaphragm wall.

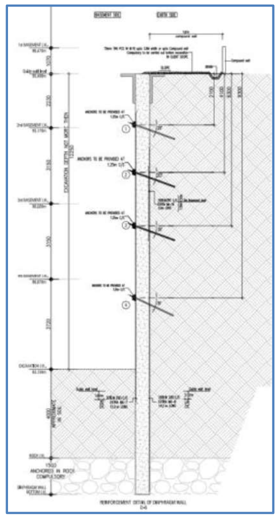


Fig 2. Drawing of panel-63

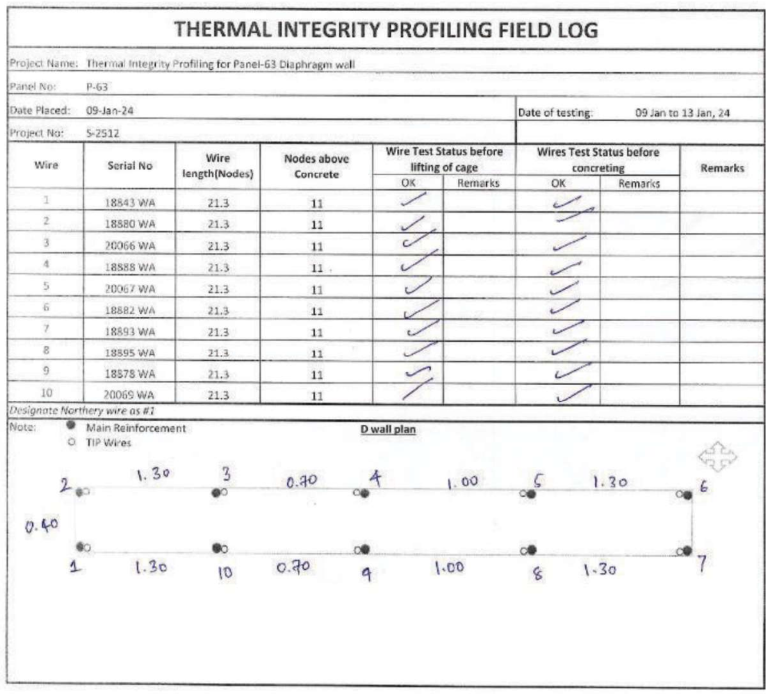
INSTALLATION OF THERMAL WIRES

Thermal Integrity Profiler (TIP) testing was conducted using thermal wire cables and thermal acquisition ports (TAPs). The TIP system assesses concrete temperatures during curing by employing cables embedded within the concrete. Each thermal wire cable has digital temperature sensors positioned every 30.5 cm along its length.

Fig.3 Thermal wires rigged up on panel-63

In this specific case, 10 thermal wire cables were installed along the entire length of the reinforcement cage. 5 wires per side uses the 1 m maximum spacing from ASTM D7949. Figure 3 presents the reinforcement cage with thermal wires during the process of lifting the cage and lowering it into the excavation. Binding wires were used to secure the thermal wires at reinforcement joint locations and cable ties were used along the length of the wires to secure the wires to the reinforcement.

A functionality check was conducted with a thermal wire tester at three key stages: before installing the thermal wires, after installation but before lifting, and after lowering them into the excavation but before the concreting process. A field log presented in Fig 4 was kept to document the positions of the thermal wires at different locations along the diaphragm wall and to confirm that all 10 thermal wires were functioning properly.



THERMAL INTEGRITY PROFILING FIELD LOG

Project Name: Thermal Integrity Profiling for Panel-63 Diaphragm wall
Panel No: P-63
Date Placed: 09-Jan-24
Date of testing: 09 Jan to 13 Jan, 24
Project No: S-2512

Wire	Serial No	Wire length(Nodes)	Nodes above Concrete	Wire Test Status before lifting of cage		Wires Test Status before concreting		Remarks
				OK	Remarks	OK	Remarks	
1	18843 WA	21.3	11	✓		✓		
2	18880 WA	21.3	11	✓		✓		
3	20066 WA	21.3	11	✓		✓		
4	18888 WA	21.3	11	✓		✓		
5	20067 WA	21.3	11	✓		✓		
6	18882 WA	21.3	11	✓		✓		
7	18893 WA	21.3	11	✓		✓		
8	18895 WA	21.3	11	✓		✓		
9	18878 WA	21.3	11	✓		✓		
10	20069 WA	21.3	11	✓		✓		

Designate Northery wire as #1

Note: ● Main Reinforcement ○ TIP Wires

Fig.4 Thermal Integrity Profiling Field Log

CONCRETING AND DATA COLLECTION

Concreting (M30 Grade) commenced after the thermal wires were connected to the TAG and TAP-EDGE data loggers and cloud configuration to access real-time data was complete. Wires 1,7, 8, 9 & 10 were placed on the Soil Face (FF - outside excavation). Wires 2, 3, 4, 5 & 6 were placed on the Excavation Face (NF - inside excavation). Wires 1 & 2 and 6 & 7 are wires on corners. The concreting was performed using the tremie method at 2 different locations within the cross-section of the panel as shown in Fig 5 and Fig 6.

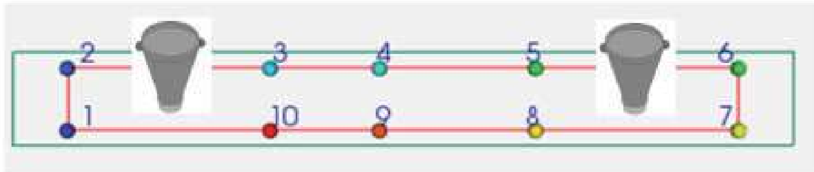


Fig.5 Configuration of thermal wires and tremie

Fig.6 Concreting using Tremie method

During the curing of the concrete, the hydrating cement generates heat, increasing the temperature in the panel. Every 15 minutes the TAG and TAP-EDGE data loggers automatically record the measured temperature at each sensor location along the length of the wire, generating a profile of temperature versus depth at each increment of time.

The TAG data logger automatically transmits the data to the PDI Cloud where the data can be monitored remotely. After the concrete peak temperature has been achieved, the data is downloaded for further analysis and reporting.

TIP DATA ANALYSIS

The TIP results may be evaluated for consistency of the panel's temperature profile and the general location of the reinforcing cage. Panel integrity may be assessed based on the average temperature measurements from each Thermal Wire at each depth increment. If the measured average temperature versus depth is consistent, the panel is considered to be uniform in shape and quality. Bulges may be identified as localized increases in average temperature, while insufficient concrete quality or cross-section reductions can be identified as localized decreases in average temperature. Anomalies over more than ten percent of the effective cross-sectional area are normally seen in multiple Thermal Wires at the same depth. Because soil and/or slurry pockets produce no heat, areas of soil intrusion or inclusion are indicated by lower local temperatures. The ends of the panel have a larger surface area in contact with soil, and will therefore be cooler than wires on the longer faces of the panel.

The reinforcement cage location can be estimated based on the relative temperature difference between an individual Thermal Wire and the average of all wires. Higher individual Thermal Wire temperatures indicate the wire is closer to the center of the panel, or near a local bulge, while lower individual Thermal Wire temperatures indicate the wire is closer to the soil-panel interface, or a local defect. By viewing diametrically opposite Thermal Wires, instances, where a lateral shift of the reinforcing cage has occurred, can be determined if one wire temperature is higher than average and the diametrically opposite wire temperature is similarly lower than average. In short, the average temperature profile (from all wires) defines the shape of the shaft and local variations from the average indicate cage offsets from center.

RESULTS AND DISCUSSIONS

The ideal time to evaluate the panel's temperature profile is generally the period between half-peak and peak temperature. For this analysis, the selected time was near peak temperature, which occurred about 27.25 hours after concrete placement. Temperature fluctuations of +/- 0.5 degrees Celsius are typically considered within the normal range for TIP results, owing to the accuracy of the sensors. Anomalies would be indicated by sudden temperature drops at certain depths. The results display the recorded temperature (in degrees Celsius) versus depth below the cutoff (in meters), with each cable's data represented by a unique color, along with the average temperature. The temperature tends to drop at the bottom of the panel due to heat loss at the concrete/soil interface, while a similar decline is observed at the top due to the concrete/air interface.

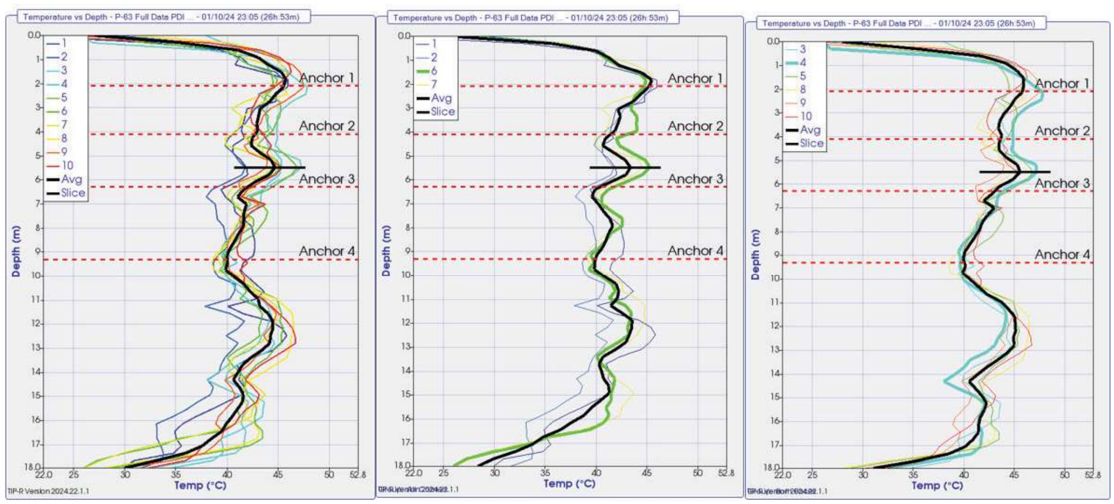


Fig 7. All wires, corners only, faces only at time of peak temperature (Left to Right)

Unlike pile foundations, where a reduction in cross-section or cover thickness can be quantitatively measured, in diaphragm walls, this assessment currently remains qualitative. It is recommended to check the temperature profiles in specific areas—such as corners, faces, the soil-facing side, and the excavation-facing side—rather than examining all the wires at once. This approach is suggested because the diaphragm wall has a rectangular cross-section, not a circular one. Figure 7 presents the temperature profiles at peak temperature.

There are observed reductions in temperature indicative of a soft bottom from 15 to 18 m, particularly in the wires measuring the four corners of the panel (Wires 1, 2, 6 & 7). The soft bottom may be due to any of the following reasons :

- Panel Length being shorter : This is not possible as the cage has been lowered to design depth and actual concrete volume is in excess of 10.5% with respect to theoretical volume.
- Presence of debris or soft muck at the cage bottom particularly at the corners
- Variation in panel geometry in the socket depth at corner locations.

The faces and corner wires indicate potential increases in cross-section at 2 m, 5 to 6 m, and 11 to 13 m. The 10.5% overpour could account for these bulges, and minor (50-100 mm) increases in the 600 mm nominal thickness of the wall are the most likely direction for the change.

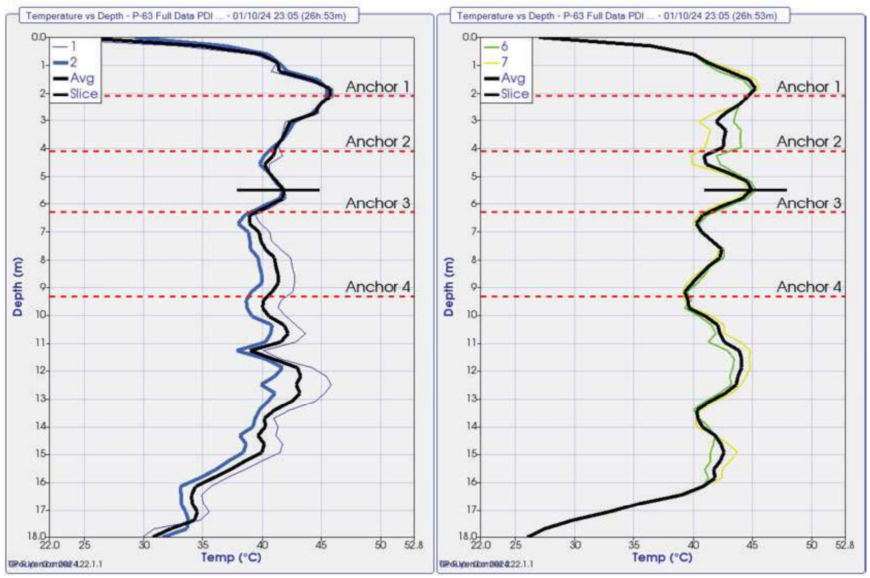


Fig 8. Left corners wires 1 & 2 & Right corner wires 6 & 7 (Left to Right)

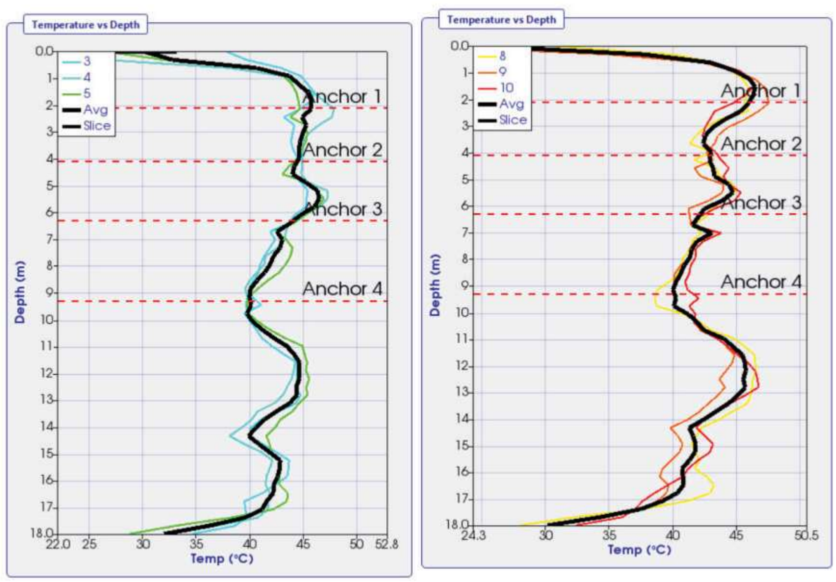


Fig 9. Soil Face-Wires 3,4 & 5, Excavation Face-Wires 8,9 & 10 (Left to Right)

Left corner wires 1 and 2 indicated minor inclusion at 11 m and reduction in concrete volume from 15 to 18 m. Right corner wires 6 and 7 indicate reduction in concrete volume from 16 to 18 m (Fig 8). Soil temperature at the base is expected to be 24 degrees Celsius in Bangalore where peak here is only 25 degrees C. Cage alignment on wire 1-2 side is less centered than 6-7 side. Anchor access duct signatures can be seen on wires embedded on the face of D-Wall as presented in Fig 9.

SUMMARY AND CONCLUSIONS

- Thermal Integrity Profiling was available for interpretation and reporting 28 hours after completion of casting.
- The faces and corner wires indicate potential increases in cross-sections at 2m, 5m to 6m, and 11 to 13m. The 10.5% excess pour could account for these bulges.
- There are observed reductions in temperature indicative of a soft bottom from 15 to 18 m, particularly in wires 6 & 7 (Right corner of the D-wall).
- Corner wires 1 and 2 (on the left) indicate minor inclusion at 11m whereas the same is not evident in other thermal wires.
- Cage alignment on corner wires 1-2 is slightly off-centered than 6-7 side which could be attributed to a minor change in cage alignment.
- There are no observed reductions in temperature indicative of major anomalies over the instrumented length as the minor inclusion around 11m is only evident in corner wires 1 & 2 and soft bottom from 15m to 18m is evident only in wires 6 & 7. Hence these anomalies are interpreted to be localized. Expected temperature reductions are observed at the anchor duct locations.
- On the left corner with wires 1 and 2, the cage alignment appears slightly shifted. The maximum temperature variation between these wires is 5 degrees, indicating a minor inconsistency.
- Hence, the Integrity of the Panel-63 Diaphragm wall appears to be satisfactory. However, the minor anomalies can be sorted when the adjacent panels and secondary panels are constructed.
- It is further recommended to verify the geometry of the adjacent D-wall panel to acquire more information on panel-63.

ACKNOWLEDGEMENTS

The authors extend their sincere thanks to the site engineers, technicians, the client, and Pile Dynamics Inc. for their invaluable support in completing the project and preparing this paper.

REFERENCES

ASTM Standard D7949-14, “Standard Test Methods for Thermal Integrity Profiling of Concrete Deep Foundations,” ASTM International, West Conshohocken, PA

Bixler, M., Belardo, D., Piscsalko, G. (2015), “Case Histories for Utilizing Thermal Integrity Profiling for Foundation Quality Assurance,” Geo Vancouver 2016, Vancouver, Canada, October 2016.

Boeckmann, A., Yeskoo, R.A., Axtell, P. (2022). “Use of Thermal Integrity Profiling (TIP) in Drilled Shaft Evaluation.” Final Report to the Missouri Department of Transportation. Report CMR 22-002.

Coleman, T. , Belardo, D. (2023). Drilled Shaft Base Quality Reductions Identified with Thermal Integrity Profiling.” Paper Presented at DFI 48th Annual Conference.

Hyatt, T., Belardo, D. and Webster, J. (2019) “Cost and Technical Comparison of Non-Destructive Test Methods for Drilled Shafts.” Paper Presented at DFI 44th Annual Conference.

Johnson, K. R. (2015). “Analyzing Thermal Integrity Profiling Data for Drilled Shaft Evaluation,” Outstanding Student Paper, DFI National Convention, Oakland, CA.

Mullins, G. and Ashmawy, A. (2005). “Factors Affecting Anomaly Formation in Drilled Shafts.” Final Report Submitted to Florida Department of Transportation.

Piscsalko, G., Likins, G., Mullins, G., (2016). “Drilled Shaft Acceptance Criteria Based Upon Thermal Integrity”, DFI 41 Annual Conference on Deep Foundations: New York, NY, pp 1-10, October 2016.

Sellountou, A., Alvarez, C., Rausche, F., 2013. Thermal Integrity Profiling: A Recent Technological Advancement in Integrity Evaluation of Concrete Piles, Proceedings from the First International Conference, Seminar on Deep Foundations, Santa Cruz, Bolivia

Stark, T.D., Idries, A, and Osouli, A. (2022). "Evaluating the Accuracy and Use of Drilled Shaft Integrity Testing Methods in Illinois", Illinois Department of Transportation, Bureau of Research.

White, B., Slomski, S. and Klausing, B. (2023) “Load Testing for Acceptance of Shafts with Questionable Integrity-Case Studies” Paper Presented at DFI 48th Annual Conference, 2023.