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A Review of Thermal Integrity Testing of Marine Piles

Chris Barker
Arup, London, United Kingdom, chis.barker@arup.com

Anthony Fisher
Cementation Skanska Ltd, Doncaster, United Kingdom

ABSTRACT: Thermal integrity testing has become one of the standard non-destructive tests used in deep foundations. The range of pile types and ground conditions which it has been employed now includes marine environments such as docks, rivers and offshore sea locations. Some of these marine locations are subject to water flow and tidal fluctuations. In these marine environments the top section is permanently cased to allow the pile shaft to be formed. The strong cooling of the submerged pile shaft exposed to water is of such significance that very little change in concrete temperature is typically recorded in the cover zone. Any assessment of pile integrity in these regions will be significantly affected by the reduction in temperature generation and will, therefore, be less effective at detecting anomalies. This paper examines several case studies of thermal integrity testing of marine piles to provide insight into best practice specification, measurement and interpreting of thermal integrity testing of marine piles.

KEYWORDS: thermal integrity testing, distributed fibre optic sensing, marine pile.

1 INTRODUCTION

Deep foundations are commonly used to support significant engineering structures like buildings and bridges. These foundations are often constructed as cast-in-situ concrete piles due to their ability to support large loads. The structural design of these foundations requires a holistic approach to reinforcement design, concrete mix design and construction methodology.

The challenging nature of casting concrete deep in the ground makes construction of these foundations at risk of structural imperfections (Sun et al. 2024). Therefore, it is common for the construction of such foundations to be verified with integrity testing.

Thermal integrity testing is an established method to assess the integrity of cast-in-place piles. This method relies on measuring the temperature of concrete in the piles during the concrete curing process. The temperature and change in temperature profiles are reviewed for temperature anomalies that may indicate either a reduction or increase in concrete volume.

For cast-in-situ concrete marine piles the top section is usually permanently steel cased above bed level (sea, river, dock) to allow the concrete pile shaft to be formed through water. The strong cooling of the pile shaft exposed to water is of such significance that very little change in concrete temperature is typically recorded in the cover zone (Fisher et al. 2025). Any assessment of pile integrity using thermal integrity profiling in these regions will be significantly affected by the reduction in heat generation and will, therefore, be less effective at verifying satisfactory construction.

This paper examines several case studies of thermal integrity testing of marine piles to provide insight into best practice specification, measurement and interpreting of thermal integrity testing of marine piles.

2 THERMAL INTEGRITY TESTING

Heat generation and its subsequent dissipation in early-age concrete are influenced by the concrete mix, the thermal conductivity of the ground and the geometry of the concrete structure, and additionally for marine piles, the surrounding water above bed level. If defects exist inside the concrete mass, they will result in local temperature variations when compared to the expected heat generated during concrete curing. As such, the measured temperature data can be used to infer the as-built shaft shape, the centrality of the reinforcing cage and the possible existence of imperfections.

This technique of thermal integrity profiling, like all other integrity testing methods, also has its limitations. The current industry data interpretation practice is primarily based on empirical experience. Anomaly detection through direct analysis of temperature profiles is currently indicative or suggestive, and short of extracting the pile, it is difficult to independently verify the interpretation. Temperature signatures are usually similar, and the potential numerous causes are not easily isolated. Moreover, the hydration process and temperature signatures vary with cement content and composition and the pile boundary conditions. The use of pile construction logs and concrete yield data in the thermal integrity profiling analysis for predicting pile radii along the shaft has been proposed by researchers (Mullins, 2010; Johnson 2016; Mullins and Johnson, 2016). In this interpretation method, the overall average temperature of the pile is used as a reference; measurements which are cooler than the overall average are areas of reduced concrete volume (or poor concrete quality) and areas with a higher temperature than the average are areas of increased concrete volume. The method translates the temperature variations from the overall average temperature, to changes in pile geometry; while this is a good starting point, it is obviously a simplification of the reality, for instance in scenarios where boundary conditions have a more pronounced influence on the measured temperature.

3 ONE NORTH QUAY

3.1 *Introduction*

This project is the construction of a 25-storey commercial concrete frame building that spans partly over the historic North Dock at Canary Wharf in London. The dock is impounded with a water level at approximately +4.2mAD and was historically dredged to approximately -5mAD although there is now a variable accumulated thickness of dock silt on the dock bed. The dock water is static. This new building will be supported on twenty marine piles of 1500mm and 1800mm diameter that were constructed between July and September 2024. Piles were permanently cased with 16m long casing with the casing top level at +6.37mAD. Piles were rotary bored under polymer support fluid and concreted with a C32/40 CIIIB+SR concrete mix with 420kg/m^3 of cementitious material, of which 70% was GGBS, cast to a level of +2.20mAD.

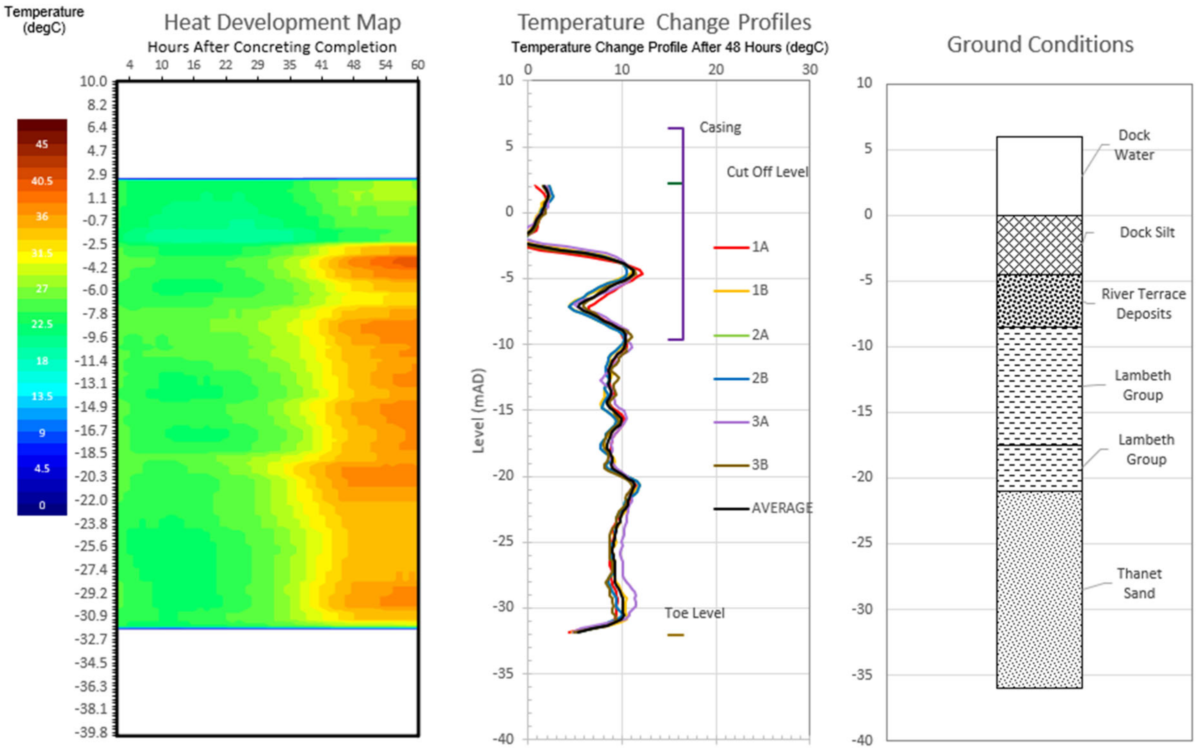

Figure 1. One North Quay marine pile CP3003 thermal integrity testing profiles (a) Heat development map, (b) Temperature change profiles, (c) Ground conditions.

3.2 *Thermal Integrity Testing*

Thermal integrity testing was undertaken using distributed fibre optic sensing with three loops of fibre optic cable deployed in the cover zone of the piles. These cables measured the heat generated by the hydration of the concrete within the first 60 hours after completion of concrete pouring.

Figure 1 shows the thermal integrity testing results for a typical 1500mm diameter marine pile. The results are presented firstly in a heat development map which shows temperature development over time, averaged horizontally across the pile. A change in temperature profile from each of the six fibre optic cables monitored, is shown in Figure 1(b). Lastly, a soil stratigraphy profile is also shown in Figure 1(c). Of interest in this paper, within the permanently steel cased section of the pile above -2mAD which were exposed to the static dock water, very little temperature change was measured within the cover zone. This effect also extended into the dock silt, which was hydraulically connected with the dock and to a lesser extent in the River Terrace Deposits at -7mAD. Consequently, with a temperature increase of only between 1 to 4°C above a level of -2.0mAD, temperature measurements for thermal integrity testing in the upper-cased part of the pile was inconclusive.

3.3 *Observations*

Above -2mAD there was a significantly reduced temperature change from the more typical 10°C increase observed lower down in the pile, after 48 hours. This is caused by increased heat dissipation into the dock water compared to the surrounding soils. Although there are no indications of reduced concrete quality within this region, the limited heat generation reduces the effectiveness of the thermal integrity test to assess the pile integrity.

4 EDEN DOCK BRIDGE

4.1 *Introduction*

Eden Dock bridge is a new 60m span pedestrian footbridge across Eden Dock at Canary Wharf, London. The dock is impounded with a water level at approximately +4.2mOD and was historically dredged to approximately -5mOD although there is now an accumulated thickness of dock silt on the dock bed up to +0.34mOD. The dock water is static. The bridge is supported on two 2.1m diameter piles that were constructed in early to mid November 2024. Piles were permanently cased with 16m long steel casing with the casing top level at +5.9mOD. Piles were rotary bored under polymer support fluid and concreted with a C32/40 CVI-SL+SR mix with 446kg/m^3 of cementitious material, cast to a cut off level of +1.15mOD.

4.2 *Testing*

Thermal integrity testing was undertaken using distributed fibre optic sensing with four loops of fibre optic cable deployed in the cover zone of the piles. These cables measured the temperature generated by the hydration of the concrete within the first 100 hours after completion of concrete pouring.

Figure 2 shows the thermal integrity testing results for the south marine pile. Within the permanently cased section of the pile above -3mOD which was exposed to the static dock water, again very little change in temperature was measured within the cover zone.

With a temperature increase of less than 5°C expected in the upper section of the pile, thermal temperature measurement was commenced from completion of cage installation, prior to concreting. The earlier commencement of temperature measurement enabled the temperature change due to concreting to be captured. The second heat development map Figure 2(b) illustrates the heat development over the first 10 hours from commencement of concreting rather than from completion of

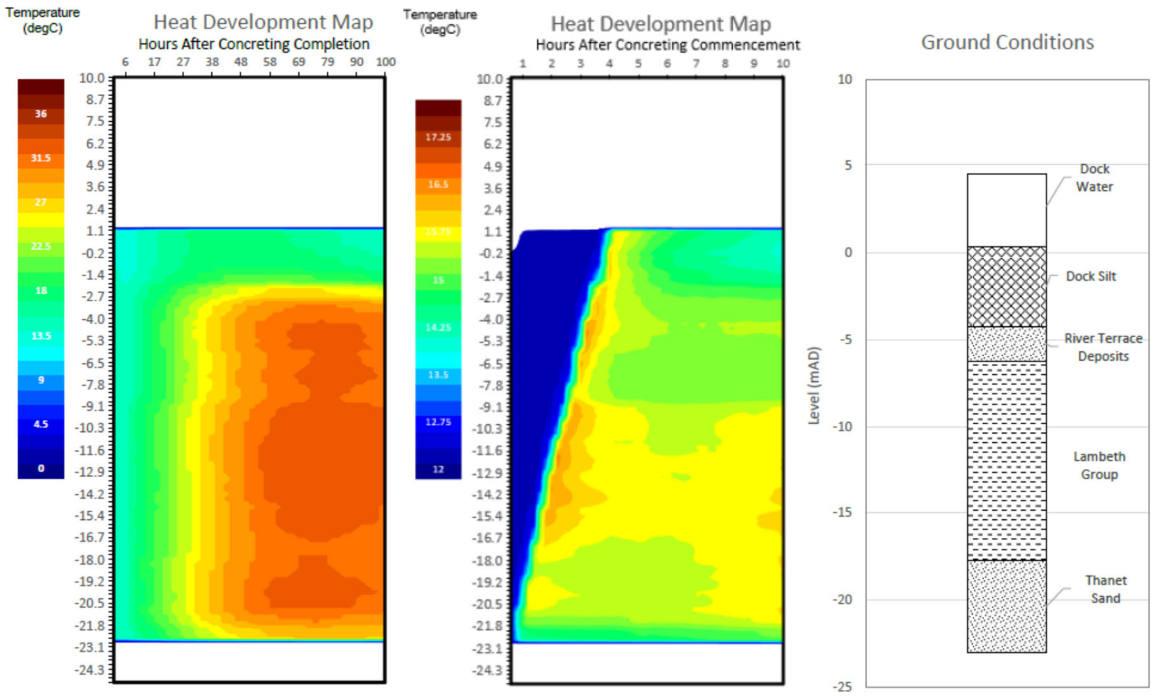

Figure 2. Eden Dock marine pile (south) thermal integrity testing (a) Heat development map after concrete completion, (b) Heat development map after concrete commencement, (c) Ground conditions.

concreting. As the 3 to 4°C increase in temperature change occurs rapidly as the fresh concrete displaces the support fluid, the regular filling of the cover zone can be seen.

For the south marine pile, the average temperature profiles from all cables from completion of cage installation, at two specific elevations of -13mOD and -1mOD, one well below and one near dock bed level of +0mOD, are shown in Figure 3. In these profiles the starting temperature represents the support fluid temperature of 12.3°C. The subsequent vertical rise in temperature indicates concreting, which has a temperature of about 16°C. The concrete in the cover zone is then momentarily cooled by the lower temperature of the surrounding ground / dock water before the heat from concrete hydration is generated. Subsequently, the soil below the dock bed has an insulating effect allowing a maximum temperature of 34°C to be achieved. However, the largely static dock water (with perhaps some slow convection) having higher conductivity dissipates the heat from hydration limiting the maximum temperature to 19°C.

The evaluation of temperature profiles over zones of low temperature generation are more effective when it also includes review of temperature versus time (Boeckmann et al. 2022), commencing from completion of cage installation.

4.3 *Observations*

Above -3mOD there was an expected significant reduction in temperature change from the more typical 18°C increase observed lower down in the pile, after 66 hours. This is caused by increased heat dissipation into the dock water compared to the surrounding soils. To enable assessment of this area, temperature measurement commenced from the completion of cage installation. The rapid change in temperature, although small, that occurs when the fresh concrete displaces the support fluid provides an illustration for review, Figures 2(b) and 3 that allows comparison of the concrete filling of the whole pile that is otherwise unseen in the upper cased section of the marine pile, Figure 2(a). Figure 3 average profiles can also be plotted for each temperature cable for local assessment of the concrete around the circumference of the pile.

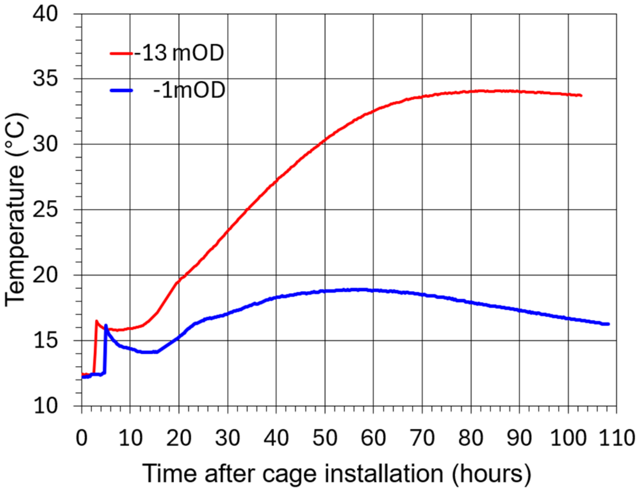

Figure 3. Eden Dock marine pile (south) development of average temperature profiles at two levels.

5 NORTH WESTERN DOCK

5.1 *Introduction*

The North Western Dock project involved the construction of a new quay wall for a marine facility in the north-west of England. The ground conditions at the site consisted of a thick layer of made ground, overlying glacial till and bedrock. The made ground comprised hydraulically placed granular material, with some sections having been further treated with vibrocompaction to mitigate liquefaction risks. The glacial till was a firm to hard cohesive material with two distinct glaciofluvial deposit layers within it. The bedrock was Sidmouth mudstone, which is part of the Mercia mudstone group. As will be shown, the different ground conditions had a significant influence on the thermal integrity testing results as well as the choice of construction technique.

Piling works included 1950mm diameter king piles. These were constructed with a 40m long, 1800mm diameter pile, bored through a 1950mm diameter, 20m long driven steel tube which was 25mm thick. The gaps between the king piles were bridged with a sheet pile to form the new quay wall. The steel tube ran from finished quay level, through the water of an existing dock and then into the glacial till. The rotary piles were bored beyond the steel tubes using polymer support fluid and installed down into the mudstone bedrock.

Behind the new quay wall, further piles were installed. Bearing piles were permanently cased at 1200mm diameter down into the boulder clay and 1650mm diameter anchor piles, were installed in pairs. The bearing piles were used to support the weight of the new facility and were constructed through made ground, placed after the king piles were installed. The anchor piles were connected to the king piles using tie rods to provide additional lateral support to the wall.

The concrete used in all of the piles was a C40/50 CIIIA mix with 450kg/m^3 of cementitious material, of which 40% was GGBS.

5.2 *Testing*

An extensive regime of testing was employed on this project. In addition to a preliminary testing regime described by Fisher (2022), all piles were subject to low strain integrity testing, cross hole sonic logging and thermal integrity testing. Additionally, multiple piles were cored through the base and the shaft to provide further assessment of quality. These cores were scanned by an optical televiewer which provides a 360 image of the core hole wall. During installation, detailed records were taken, including as built diameter profiles for some piles using a sonic caliper instrument.

5.2.1 *Low strain integrity testing*

Low strain integrity testing was carried out using the pulse echo technique where an accelerometer placed on the pile head measures its acceleration in response to an impact blow. As the pulse wave moves down the pile, changes in impedance along its length (changes in diameter or material density) return reflections to the surface, resulting in movements which are detected by the accelerometer.

Given the large diameter of the piles tested and the density of the reinforcement, it was not anticipated that the signal would be able to reach to toe of the pile without attenuation to below a detectable level. This proved to be the case, with no low strain integrity testing result picking up a response from the toe level of the pile. The low strain testing was seen as an additional measure to investigate the integrity of the pile head which, for reasons to be discussed, was difficult to assess from the cross hole sonic logging and thermal integrity testing. No anomalous results were identified from the low strain integrity testing.

5.2.2 *Cross hole sonic logging*

Crosshole sonic logging (CSL) involves measuring the transit time and signal attenuation of an ultrasonic wave as it travels through the concrete between a transmitter and a receiver. The sensing instruments are lowered into the pile through steel reservations tubes which are cast in with the reinforcement. By raising the transmitter and receiver at a controlled rate whilst measuring frequently, a continuous profile of measurements, often presented as a waterfall plot, is created. The king piles contained 5No such tubes, which was all that could be fitted within the cage, making allowance for the seismic hooks and other structural details.

Crosshole sonic logging of the upper sections of the shaft was hampered by the presence of a “T Head” within the core of the pile. This was a steel box out, including a 120mm thick steel washer plate that facilitated the connection of the tie rod between the king piles and the anchor piles. At the position of this element, the CSL traces consistently showed an increase in first arrival time of more than 20% and a corresponding reduction in relative energy. Interpretation of the results was also made more difficult due to uneven tube spacing and access conditions (which made it difficult to ensure an equal rate of lift between the probe and the transmitter.)

Multiple anomalies were identified by the cross hole sonic logging, most of which were determined not to be flaws or defects by consideration of the impairments to the test described above, re-testing once the concrete had gained more strength, or by comparison with other testing methods.

5.2.3 *Coring*

The coring requirement was to sample 20% of the total pile length for the first 10 piles and then 5% of the remainder, unless anomalies were detected, in which case further coring would be required. Core holes were 75mm in diameter and cut using rotary diamond core drilling. Coring for the full length of the piles was not possible due to the risk of non-vertical drilling cutting into the reinforcement. Consequently, cores were taken through reservation tubes installed to various depths in the piles to be cored.

Compressive strength testing was carried out, with one sample tested for every 5m of coring. Cores of the pile base were taken over the bottom 1m of the pile and extending to two pile diameters length into the rock.

Within the lined shafts of the king piles, around 100m of concrete was cored and no flaws were found. All strength testing was in excess of the design requirements. On several piles, including the two anchor piles presented in Figure 4, CSL and TIP identified anomalies from the results at the pile base which were not apparent in recovered core samples. This may have been due to the central location of the core sample when compared to the other test methods. In these cases, acceptance of the piles was gained through evaluation of the design requirements compared to the as-built pile lengths alongside pressure grouting of the bases.

5.2.4 *Thermal integrity testing*

Thermal integrity testing was carried out using distributed fibre optic sensing with loops of fibre optic cable deployed in the cover zone of the piles. Three loops of cable were installed within the king piles and anchor piles and two loops installed in the bearing piles. This provided parity with the CSL and is standard practice in the UK (1 loop of cable per 600mm of pile diameter).

Some of the results of the thermal integrity testing are presented in Figure 4 in which the typical temperature changes measured between the completion of concreting and reaching peak temperature are overlaid onto a drawing of the piles and geology.

Thermal integrity testing within the glacial till and the rock provided useful data on pile integrity and showed good correlation with sonic caliper and concrete overbreak results. In particular, within the glaciofluvial deposit layers and even occasionally within the glacial till there were zones of significant overbreak which could be seen by increases in

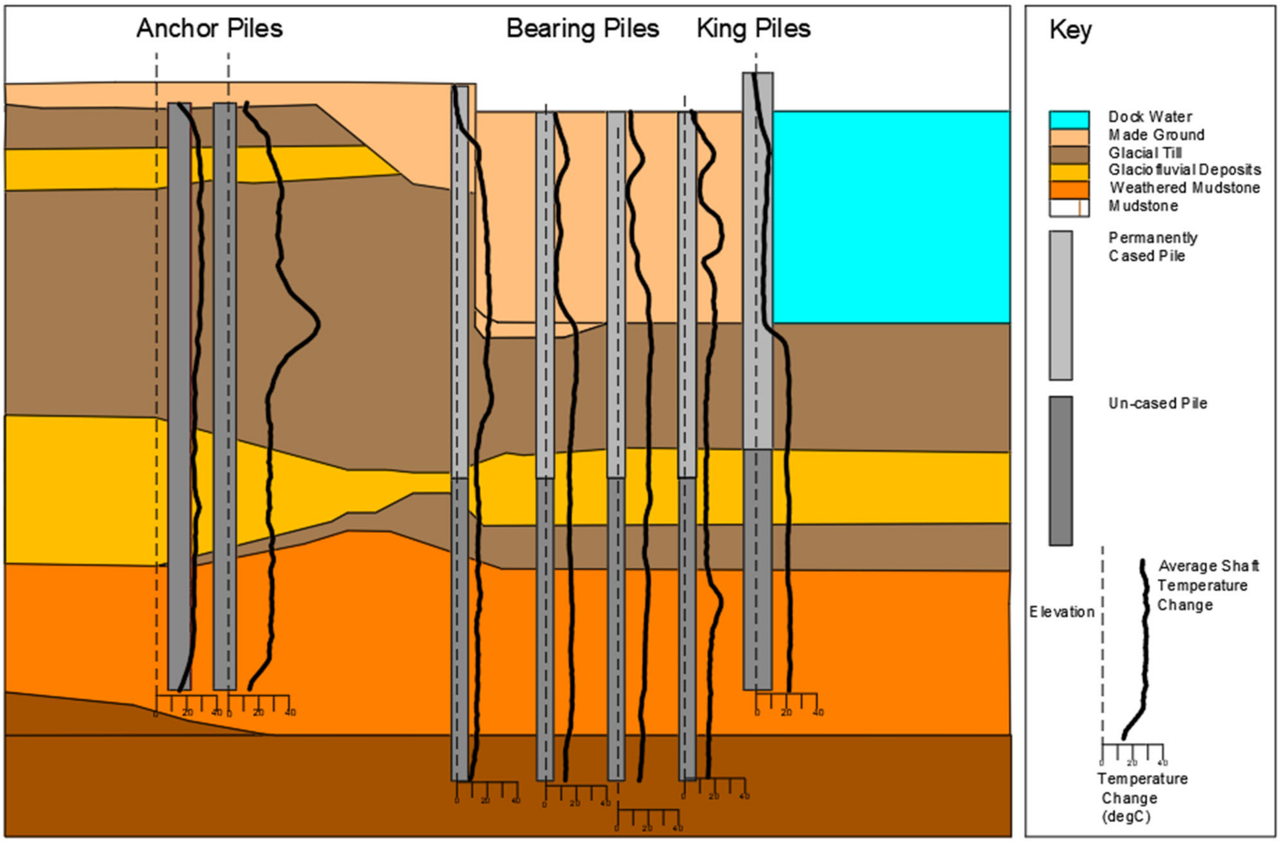

Figure 4. North Western Dock temperature change profiles

temperature change. An example of such a feature is presented in the anchor piles in Figure 4. In this case, the correlation between the concreting records and thermal integrity testing results gave confidence that the feature was overbreak and not detrimental to pile performance. Temperature measurements near the toe of the pile and from the loop of fibre optic cable around the bottom of the reinforcement cage provided valuable information about the base of the pile which could be further correlated with CSL and coring.

Within the permanently cased sections of the pile which were exposed to the dock water, very little temperature change was measured within the cover zone. This effect also extended into the granular Made Ground deposits which were hydraulically connected with the dock. Consequently, thermal integrity testing in the upper parts of the pile was not conclusive.

5.3 *Observations*

The most challenging part of the integrity testing on this project was interpreting the results of the test carried out in the upper portions of the piles, especially within the permanently cased zones that were exposed to the dock water. Within these regions, thermal integrity testing results were inconclusive due to the rapid dissipation of heat within the cover zone. The cross hole sonic logging results were also hard to interpret due to irregular positioning of tubes, structure details within the piles and some practical details associated with carrying out the test over water.

However, within these zones, the risk of inclusions coming from the ground was eliminated by the presence of the casing and the risk of inclusions rising up the pile was also deemed to be lower. The use of low strain integrity testing (although the penetration of the test was uncertain), and coring provided supplementary data points with which the integrity of the piles could be assessed.

Construction records were essential to demonstrate material properties and good concreting technique.

In other parts of the pile, there was good agreement between the testing techniques, once the variability in the ground conditions, test methods and pile geometries were accounted for.

6 ILLINOIS BRIDGE

6.1 *Introduction*

This project is the construction of a new twin multi-span bridge for the replacement of the existing ‘Chain of Rocks’ bridge that carries the I270 over the Mississippi River in Madison County, Illinois in the United States of America.

The eastbound bridge works included 75 drilled shaft foundations, each featuring 9-foot (2.75m) diameter shafts with rock sockets. Permanent steel casing was installed into the top of rock and the drilled shafts were excavated under polymer support fluid.

Eastbound Pier 12 is located mid river and includes three 9-ft (2.75m) diameter permanently cased drilled shafts with 8.5-ft (2.6m) diameter rock sockets, Shafts 12N, 12M, and 12S. Thermal integrity testing was carried out using the thermal wire method (TIP). Each shaft includes eight thermal integrity wires and eight Crosshole Sonic Logging (CSL) access tubes. All three eastbound Pier 12 drilled shafts were constructed during winter in December 2023. Atmospheric temperatures generally varied between 50°F (10°C) to 65°F (18°C) while the average river water temperature was 40°F (4°C).

At eastbound Pier 12, the geology encountered below river bed was 3 ft of sand overlying bedrock of initially 4ft slightly weathered hard sandstone overlying slightly weathered hard limestone.

6.2 *Testing*

TIP was carried out using thermistor wires in four loops. Immediately after completion of concreting all the TIP wires were between 55 to 60°F over the full length of the shaft.

The temperature profile at 66 hours after concreting shaft 12M is shown in Figure 5, TIP testing measured significantly cooler temperatures in the zone surrounded by the flowing river water. Within the rock socket and above river level, the temperatures were higher. Although there are abrupt changes in temperature at the air-to-water and water-to-soil/rock interfaces, the temperatures are relatively consistent with depth in each of the rock sockets and above river level zones. However, there is significant variation in temperature between the individual wires which is most pronounced in the zone surrounded by flowing river water. This general TIP signature was also seen in other piles.

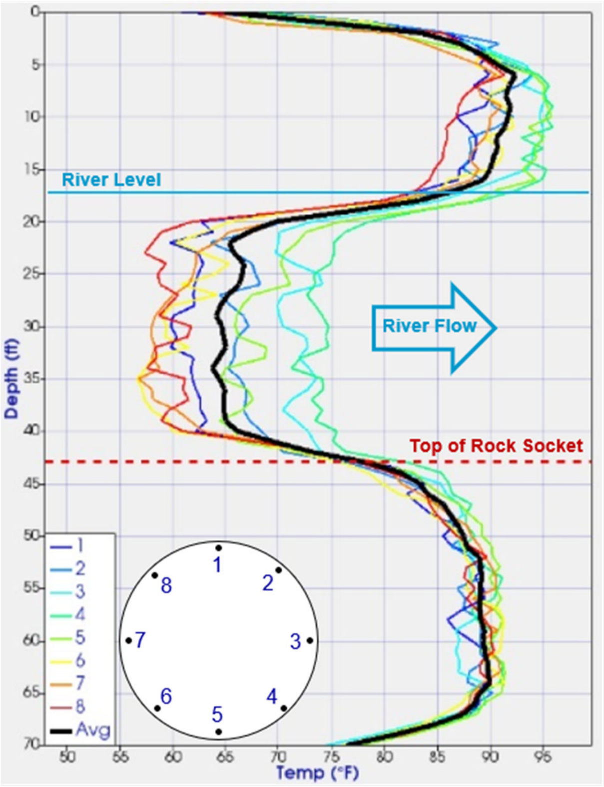

Figure 5. Drilled shaft 12M TIP peak temperature with depth

The temperature versus time curves were reviewed and considered consistent with normal hydration curves.

The drilled shafts also had crosshole sonic logging (CSL) undertaken from eight tubes spaced equally around the inside of the reinforcement cage. The 12M shaft results for profiles between tubes around the circumference of the cage appeared normal however, in up to ten diagonal profiles across the centre of the 9-foot diameter shaft Class C zones defined as highly abnormal CSL results by DFI, 2019 with a maximum energy decrease of 12 dB and a maximum FAT increase of 67 percent, were reported in the upper 44 feet (13.4m) of the shaft.

6.3 *Observations*

The flowing cold winter water temperature of the Mississippi River had a significant effect on the thermal measurements reported by the TIP wires in the cover zone. Firstly, the submerged temperature development from the hydration of the concrete was subject to strong cooling and secondly, this cooling effect was more pronounced on the upriver side of the shaft (Wires No. 1, 6, 7 & 8) due to the river water flow.

Where flowing low temperature water is present during concreting care is required during construction as concrete elements of large dimensions are especially susceptible to reaching high temperature gradients, Grabowski and Mitew-Czajewska (2021). A better understanding of the influence of early-age thermal-shrinkage in deep foundations is necessary as when sufficiently high thermal strains are reached, the tensile capacity of concrete can be surpassed leading to early-age thermal-shrinkage cracking.

7 CONCLUSIONS

The marine pile case studies presented have shown that the presence of water around a pile has a significant cooling effect on thermal integrity testing which is exacerbated when the water is flowing. Whilst it is most pronounced within sections of a pile directly exposed to the water, similar effects within hydraulically connected strata can also influence the temperature measurements in the cover zone.

These reduced temperature profiles are a consequence of the environment that the concrete pile is being cast in and not necessarily an indication of a defect. The necessity for a more nuanced analysis of thermal data is not removed by the deployment of multiple test methods, however, the combination of different methods with thermal measurements can be beneficial in understanding and interpreting the results.

For best practice specification, measurement and interpretation of thermal integrity testing of marine piles, it is important for: (i) thermal integrity testing measurement to commence from completion of cage installation so that the concrete filling effect can be recorded and assessed, (ii) evaluation of temperature profiles is more effective when it also includes a review of reported temperature versus time profiles, and (iii) measurement of temperature in the pile core.

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