Data Interpretation Framework for Pile Thermal Integrity Testing

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Abstract

Given the inherent nature of how deep cast in-situ concrete foundations (piles and diaphragm walls) are constructed, evaluating their integrity is difficult. Several well-established methods for testing integrity have been established, but each has its own advantages and disadvantages. In recent years, a new integrity test method called thermal integrity profiling (TIP) has been put into use in deep foundation construction. The primary characteristic utilised in this test is the early-age concrete release of heat during curing; abnormalities such as voids, necking, bulging, and/or soil intrusion inside the concrete body lead to local temperature fluctuations. During concrete curing, temperature sensors installed on the reinforcing cage collect precise temperature data along the entire pile, allowing empirical identification of these temperature variations. This paper proposes a staged data interpretation framework for pile integrity assessment, with the thermal integrity test serving as the initial step. The framework, which is adaptable to different concrete mixtures and pile designs, utilises the heat of hydration and the theory of heat transmission, as well as numerical modelling with the Finite Element (FE) method. It also adopts a staged procedure to assess the *as-built* quality; for a particular pile, more details are revealed about any anomalies being investigated (including location, size and shape) at each subsequent stage. The primary advantage of this staged process is that it enables practitioners to follow a risk-based approach and decide whether or not to pursue subsequent stages of construction depending on the results they get at the end of each stage. This provides practicing engineers with vital information about the quality of the pile immediately after pile building, so permitting immediate and less expensive repair and remedial work if required.

Keywords: Thermal Integrity Test; Pile Anomaly Detection; Structural Health Monitoring; Non-destructive Test

1 Introduction

Pile foundations transfer loads deep into the ground where it is stronger and stiffer. Hence, they are commonly employed in construction practice to avoid the weaker soils closer to the surface. In developing pile systems, designers must evaluate how *as-built* construction works are compared to performance specifications. Understanding the integrity and quality of these piles is a significant challenge – not least because they are buried in the ground. In recent years, pile repair and the associated maintenance accounted for a significant part of the construction cost. In the United Kingdom, infrastructure repair and maintenance costs account for approximately £15 billion each year – 20% of the total construction costs (*Infrastructure UK*, 2010). It is therefore very important to assess the quality of the piles at/during their construction. However, as underground structures they have limited accessibility which makes it very difficult to inspect the structural quality (Matsumoto et al., 2004; Kister et al., 2007). Anomalies in piles or other deep members could lead to structural instability and/or other durability problems. Studies on about 10,000 bored piles, conducted in the United States and Germany, showed that more than 15% of pile test results had signs of minor defect signs and 5% of tested piles had major defects (DiMaggio & Hussein, 2004; Brown & Schindler, 2007). The discovery of these defects could result in large financial losses and could cause undue delays. It is therefore very important to identify the pile construction defects early on, particularly when heavy loads are involved.

In the last decade, a new integrity assessment test called thermal integrity profiling (TIP), has been employed by the piling industry. It monitors the temperature changes and thermal profiles of early age concrete throughout the casting and curing processes. The heat production and dissipation within the pile concrete body are influenced by the design mix of the concrete, the nature of the ground and the pile geometry. If defects are present inside the pile, they will cause local temperature fluctuations relative to the predicted heat produced during the curing process. The observed temperature information is utilised to deduce the *as-built* shaft shape, the position of the reinforcement cage and eventually the presence of defects. The current practice of data interpretation of this temperature-based integrity method is mostly based on empirical experience in the piling industry. The detection of anomalies by directly interrogating the temperature profiles can only provide suggestive results. Temperature signal changes are similar, and it is not easy to separate the potentially many causes behind these changes.

This paper presents a staged-based framework to interpret the temperature data obtained from the field thermal integrity test. The proposed data interpretation framework employs Finite Element (FE) numerical modelling to systematically study the pile *as-built* quality through one-dimensional and two-dimensional analyses. Following this staged investigation procedure, the integrity information, such as overall quality, defect location, defect size and severity, along the pile are identified and evaluated. The detailed staged data interpretation method is explained in detail in this paper and demonstrated through a field case study.

2 Staged Data Interpretation Framework

The thermal integrity method utilises the exothermic characteristic of the cement hydration process. The generated hydration heat increases the concrete temperature. Defects within piles, such as necking, inclusions or segregation, produce less heat and therefore lower the concrete temperatures; in contrast, bulges in the shaft lead to higher concrete temperature.

In order to numerically evaluate the pile integrity using monitoring temperature data, a staged data interpretation framework is proposed as illustrated in Figure 1. The first stage is to conduct the field thermal integrity test – this comprises collecting continuous temperature data from sensors installed before casting along the entire length of the pile. Following that, a cement heat-of-hydration test (Calorimetry) should be conducted in order to provide input for the cement hydration model, which will be employed by the FE model in the later stages. Upon obtaining temperature data and ground information, the data interpretation process is then followed as follows: Stage 1, the “vertical scanning” stage, employs a 1D finite element model to perform a quick evaluation of all temperature data along the pile length. Through this scanning process, the maximum temperatures at the respective sensor locations are converted into pile effective radii, which are then used to generate a 3D pile shape for more intuitive identification of potentially defective regions. A more detailed explanation for the 1D finite element process and the pile effective radii are presented in (Sun et al., 2022).

Assuming that potentially defective regions are identified in Stage 1, the investigation moves to Stage 2, the “slicing” stage. Temperature development data is extracted from cross-sections within the defective regions and the defect investigation is performed using a 2D FE model. The information retrieved from Stage 1 is used for setting up (a) an initial defect configuration (assumed size and location) and (b) suitable search zones within the cross-sections. A series of 2D FE simulations for the heat-of-hydration are then conducted, taking into account the appropriate boundary conditions, with the temperature development data from the model then compared with the actual field data using an appropriate cost function (Δ). It is worth mentioning that more sensors (measuring points) within the cross-section provide better results.

At the end of each 2D simulation, based on the comparison with the field data, the assumed defect configuration (size and location) is optimised within the search zones through algorithms (such as differential evolution and/or particle swarm optimization) before a new 2D simulation is conducted. This is continued until the cost function is minimised to an appropriate value. The defects are assumed to be circular in shape; however, this is not the case in practice. Nonetheless, the proposed framework is not limited by this assumption as different shapes and different sizes could be assumed instead within the cross section seeking to minimise the cost function as much as possible. More detailed explanation for the 2D finite element analysis can be found in (Sun et al., 2020). The detailed procedure of the staged method will be demonstrated using a field case study in the following sections.

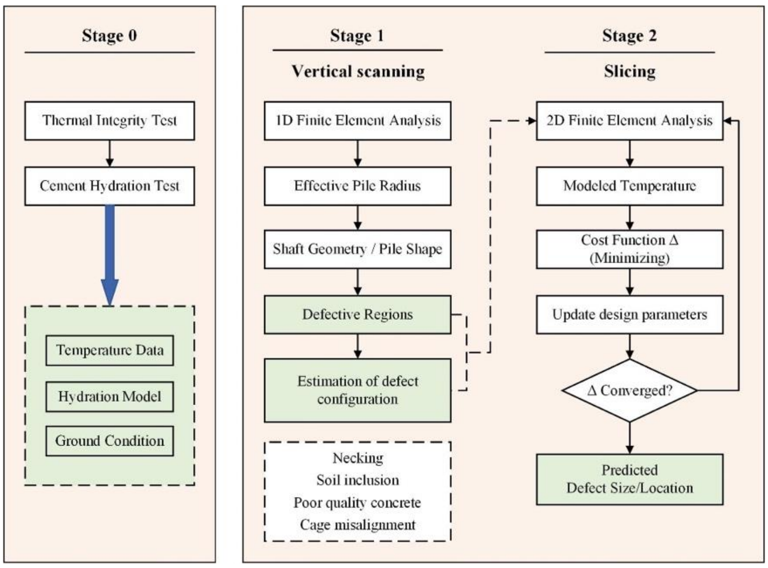


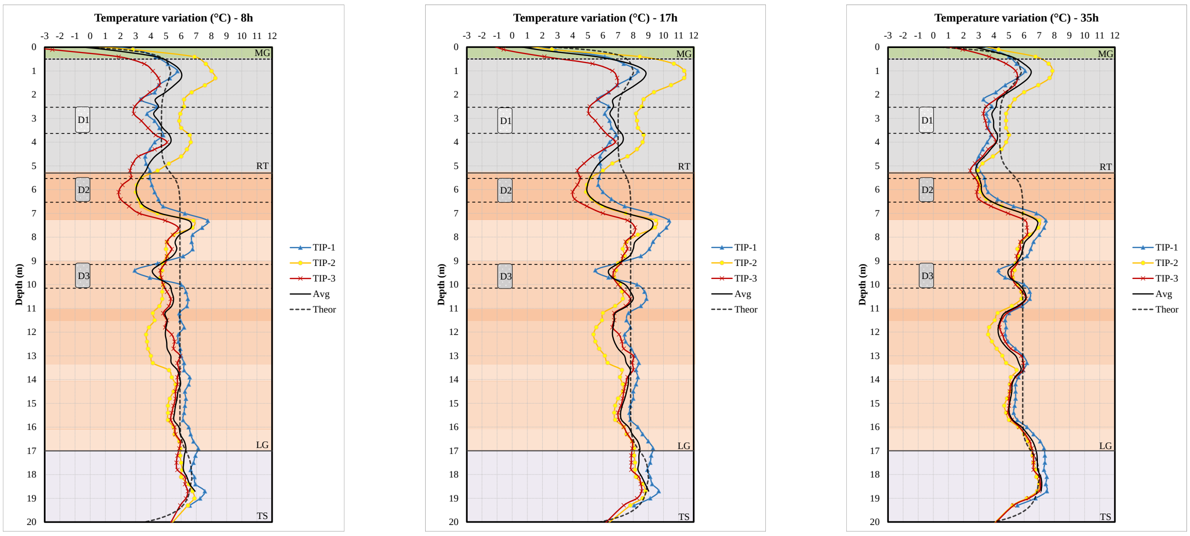
Fig. 1: Staged Data Interpretation Framework

3 Field Trial Pile Data Interpretation

3.1 Pile Instrumentation and Measured Temperature

This field case study investigated the monitoring of a continuous flight auger test pile designed to evaluate the capability of thermal integrity testing. The test pile had an exterior diameter of 900mm and a height? of 20m. Before casting concrete into the pile, temperature sensors were installed inside the reinforcing cage, which had a 750mm diameter. A total of three temperature sensing cables were installed at equal intervals; these are designated as TIP-1, TIP-2, and TIP-3 in the following text.

The measured longitudinal temperature fluctuation profiles are illustrated in Figure 2. The whole pile started to heat up between 4 and 8 hours after casting, with the exception of the top half meter, which was exposed to ambient air overnight. Seventeen hours after casting, the pile temperature peaked at between 8°C and 11°C. The temperature reduced at a fairly moderate rate after that such that 35 hours after casting, the average temperature was around 5°C for all three profiles.



(a) (b) (c)

Fig. 2: Temperature Profiles at **(a)** 8 hour **(b)** 17 hours **(c)** 35 hours

3.2 The Stage One Analysis

The first stage of the analysis involves using a 1D finite element model to quickly evaluate all temperature data along the length of the pile. This stage, also known as the vertical scanning stage, aims to assess overall pile quality and identify any defective zones for further analysis. The observed temperature at the sensor position is influenced by several parameters, such as shaft diameter, boundary conditions, and the presence of anomalies, which make it difficult to distinguish between individual elements. Therefore, changes in the temperature profile in each layer of soil are interpreted as changes in the effective pile radius, i.e., the radius of an intact pile that generates the same temperature readings at the sensor position. The effective pile radius is an important parameter for quality assurance, as it enables engineers to quickly determine whether extensive integrity studies are necessary. The effective pile radius can be linked to the effective pile cover thickness using the equation $R_{eff}=r_{cage}+D_{cover}$, where r_{cage} is the radius of the reinforcement cage.

All temperature profile variations are assumed to result from changes in the effective pile radius, which is estimated using one-dimensional finite element studies of heat transport in three radial directions corresponding to the three sensor sites inside the pile. The effective pile radius is modified at various positions along the pile depth to achieve a satisfactory match between the observed temperature profile and that estimated by the FE analysis. This approach enables the prediction of the effective radius along the depth of the pile in three sensor radial directions. After analyzing all cross-sections, the pile's geometry can be calculated.

Figure 3 illustrates a theoretical relationship between cage radius, shaft radius, and temperature at 16 hours after concrete pouring. The relationship was obtained through numerical simulation of early age concrete hydration heat development. The theoretical temperature measurement changes linearly as the shaft radius moves around the designed value, with the intersection of the solid and dotted lines representing the theoretical temperature measurement. The temperature measurement at the cage position is particularly sensitive to the concrete cover thickness, which may serve as an excellent signal for evaluating the *as-built* pile shape. Normally, pile concrete cover thickness would vary between 25mm and 200mm, with or without defects, so the measured temperature should fall within the linear zone.

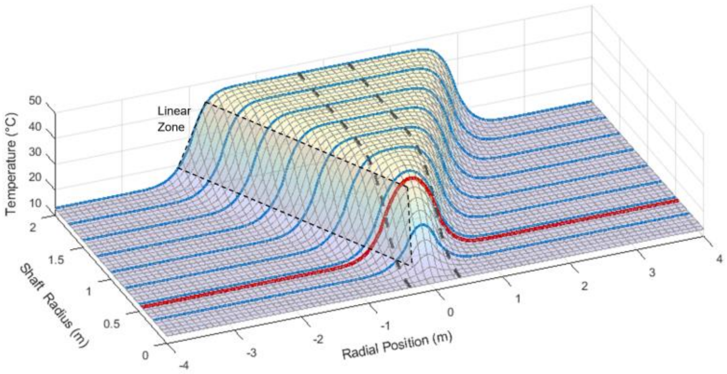


Fig. 3: Relationship between cage position, shaft size and temperature measurement at 16 hours

A strongly linear relationship is revealed through 1D FE analysis, which can be expressed in the following equation:

$$\mathrm{D_{cover}} = \alpha_k * \mathrm{T_{max}} - \beta_k \quad (1)$$

where $\mathrm{D_{cover}}$ represents the concrete cover thickness (cm) and $\mathrm{T_{max}}$ denotes the maximum temperature (℃) at the measurement point, α_k (cm/℃) and β_k (cm) are D-T parameters dependent on factors including sensor location and soil material. The values of these parameters were obtained through linear regression of the FE analysis data. In the primary body of soil (Lambeth Group), the values are α_k= 1.53 cm/℃ and β_k= 34.49 cm. Different soil layers would have different D-T parameter values. The obtained relationship allows the back-calculation of the cover thickness at three different sensor locations on the cross-sections along the pile depth. The effective pile radius can be subsequently obtained by adding the reinforcement cage radius.

Figure 4 demonstrates the 3D pile shape according to the calculated effective radius method. An expanded pile radius zone (larger than the average) is indicated in orange while the blue color indicates zones of pile radii that are smaller than average. The following could be seen from the figure:

- Two small deficient zones - between 2 to 4 m and 9 to 12m.
- One severely deficient zone - between 6 to 8 m.
- The pile radius ranges from 43 to 57 cm in the upper half while the lower half is consistently around 51 cm in radius.

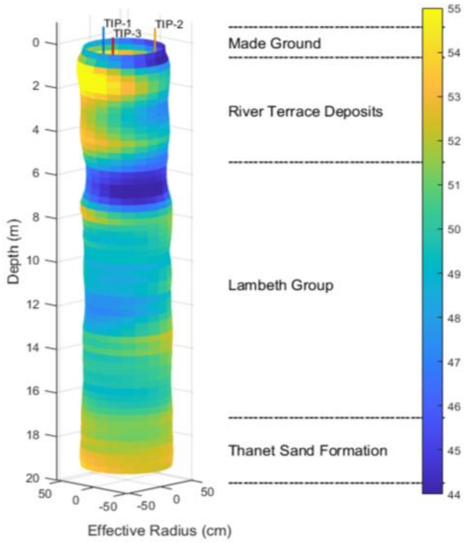


Fig. 4: Predicted pile 3D shape

3.3 The Stage Two Analysis

The 2D FE analysis in this stage aims to find the detailed defect location and size within each defective zone identified in the first stage. In this stage, known as the “slicing stage”, the defective zones are cut into multiple cross-sections to evaluate the defects at two-dimensional level. Normally, if the *as-built* pile geometry is uniform and no defects are present, the temperature profile measured at depth for each one of the cables should be similar, the temperature development at three sensors within the same cross-section should be relatively similar. The temperature data at each cross-section can be a good indicator for pile integrity at the corresponding level. As shown in Figure 5, if a defect is located near sensor 1, the measurement temperature development should be lower than the expected values, owing to a loss of heat source. For those sensors away from defects, the reduction of temperature measurement should be insignificant, such as sensor 3 in the figure. Based on that, a search zone (using a grid) is then introduced around the expected defect location and a series of FE simulations are run in a systematic manner changing the radius of an assumed circular defect centered at each of the search grid points.

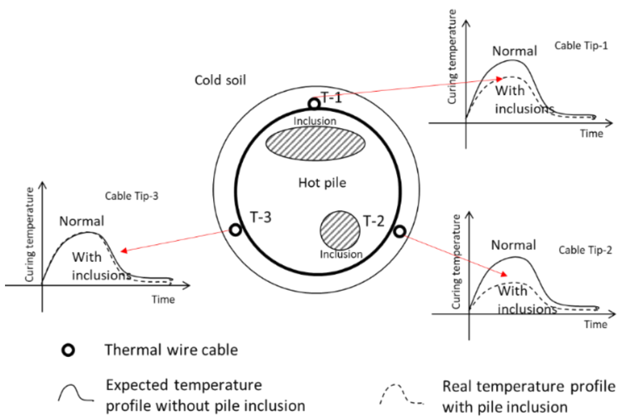


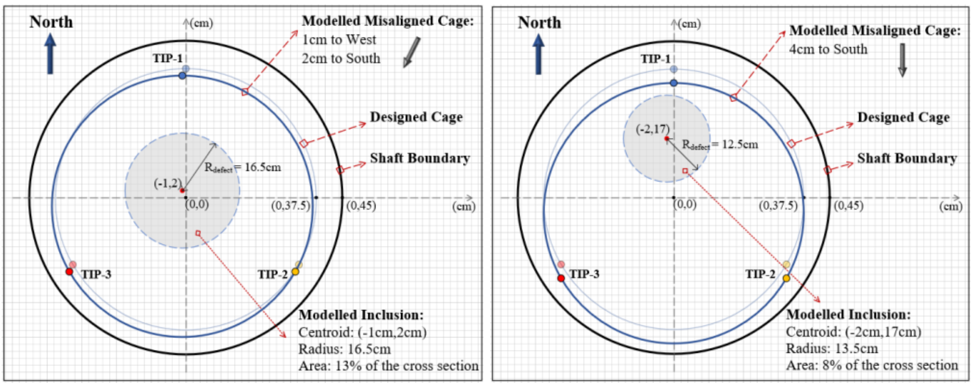
Fig. 5: Conceptual relationship between temperature development and pile integrity

A comprehensive assessment of anomalies is detailed below:

a. A numerical model is established for each cross-section at various depths within the pile depth, accounting for potential anomaly locations identified in the first stage analysis.

b. Temperature measurements from the three cables within each cross-section can provide an indication of the position of an assumed circular anomaly. For example, if a cable shows a larger temperature decrease compared to the other two at a certain depth, it suggests that the anomaly is inside the reinforcement cage and closer to that cable.
c. Based on the estimated defect locations, a starting "search origin" is determined for each cross-section. For instance, the origin is set at (0,0) for the section at 6m depth and at (0,19cm) for the section around 9m depth, as shown in Figure 6.
d. A search grid is established around the search origin for each cross-section. 2D FE simulations are then run in a systematic manner with a circular anomaly of varying radius centered at each point in the search grid zone.
e. After each simulation, the predicted temperatures at TIP-1, TIP-2, and TIP-3 are contrasted with the field measurements. The temperature difference, cumulatively, is minimized to obtain the cost function.
f. In order to consider reinforcement cage misalignment, a search zone is established within the numerical model for TIP-1, TIP-2, and TIP-3.
g. At a given cross-section, at the end of FE simulations the anomaly configuration that minimized the cost function consititutes the detected anomaly. The analysis takes cage misalignment into account.

The outcomes of the 2D FE defect forecasts at depths of 6.1m and 9.4m are depicted in Figure 6. At the 6.1m cross-section, a circular anomaly was detected with an assumed center at (-1cm, 2cm) and a radius of 16.5cm, accounting for 13% of the cross-sectional area. The cage eccentricity was found to be 1cm to the west and 2cm to the south. At the 9.4m cross-section, the FE simulation predicted an inclusion center at (-2cm, 17cm) with a size of 8% of the cross-section and a cage eccentricity of 4cm to the south. The stage 2 FE analysis provided an accurate prediction of the size and location of Inclusions 2 and 3. However, compared to the actual size of the engineered inclusions (9% cross-sectional area), the area for Inclusion 2 was slightly underestimated by 1%, while the FE analysis overestimated Inclusions 3 by 4%. Inclusion 1 was not detected in the FE studies, as it was simulated using four sandbags to mimic an externally attached concrete cover defect on the reinforcement cage. According to the on-site engineer, these sandbags were damaged during the reinforcing cage installation process. At this depth, sand spreads within the concrete body. As the volume of sand was negligible, totaling only 3% of the cross-sectional area of the pile, the concrete quality did not appear to have been considerably harmed.



(a) **(b)**

Fig. 6: Predicted Anomaly Configurations at **(a)** 6.1m, **(b)** 9.4m

In the work presented in this paper, the anomalies are assumed to be circular in shape; however, in practice, the flaws have different shapes and may consist of low-quality concrete. This does not restrict the methodology proposed above. Different shapes (of varying sizes) may be assumed in the studies, and more shapes (of varying sizes) could be gradually added inside the same cross-section to reduce the cost function and get the best possible outcome. In addition, a new technique of topology optimisation has been devised to discover faults in both 2D and 3D space. It can evaluate the quality of concrete in a precise manner and predict defects in any shape. The details can be found in the authors' future publications.

4 Conclusion

A relatively new and promising technique for assessing thermal integrity involves measuring temperature changes induced by hydration heat. In this paper, a framework for interpreting data from the test is proposed, and a case study of the test is presented using this new approach on a trial pile.

The stage one analysis uses a 1D finite element analysis to interpret the data while accounting for the parameters of the concrete mix and soil. The FE model establishes a linear relationship between maximum temperature and effective pile radius. The pile effective radii throughout the whole shaft could be determined using the linear relationship, and the expected *as-built* pile's 3D shape could then be recreated, making it possible to more effectively identify problem areas. After that, the stage two analysis, which used 2D finite element analysis, was able to accurately estimate the sizes and positions of the anomalies with less than 10% of the cross-sectional areas of the sections under consideration.

More information regarding the defects, such as their position, size, and shape, can be disclosed in each stage. This staged procedure enables practitioners to take a risk-based approach and choose whether or not to go on to the next stage based on the data they get at the conclusion of each stage. This innovative method may provide practicing engineers with vital test data about the quality of the pile immediately after pile building, so permitting immediate and less expensive repair and remedial work.

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