Flaw detection threshold of thermal integrity testing

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ABSTRACT

The thermal method, based on measuring the hydration temperatures of fresh concrete, is the latest one devoted to testing the integrity of bored cast in situ piles (drilled shafts). Unlike other methods, it is claimed to cover the whole volume of the piles, both inside and outside of the rebar cage. The flaw detection capabilities of the method are still undecided, having been established by a small number of controlled site tests. This document describes a new numerical method that can simulate the thermal behavior of newly-cast piles of any shape and under any boundary conditions. The results of a few situations modeled prove that under worst-case scenarios the thermal method is unable to establish the integrity of the pile skin and may even totally miss a complete discontinuity. It is shown that the method still requires extensive improvements to qualify as a dependable, user-friendly tool for testing the integrity of concrete piles.

Keywords: Bored piles, finite differences, Integrity testing, flaws, defects, thermal

1. INTRODUCTION

During the last decades, with the growing demand of high-rise buildings and large bridges, cast in-situ bored piles have grown in size, and diameters of three meters and more have become commonplace. Due to the high loads such piles carry they usually offer no redundancy, thus their structural integrity is mandatory. However, experience has proven that with all due care such foundation elements may have flaws that detract from their performance. Large-scale studies on piling sites have found that 33 to 38 percent of the piles tested had one or several flaws, with almost 90 percent of the flaws concentrated in the upper and lower thirds of the pile (Jones and Wu 2005, Camp et al. 2007). In view of these statistics, there is now a consensus among engineers that all bored piles need to be tested for integrity

Cross hole sonic logging (ASTM 2016) has evolved to become the predominant method for testing bored pile integrity. The method provides a high-resolution map of the element in 1, 2 or 3 dimensions but is basically limited to the volume bounded by the reinforcement cage.

The thermal method, recently developed, utilizes the heat developed during concrete hardening to assess the integrity of bored piles shortly after concreting (ASTM 2014). The method is based on measuring the concrete temperatures at the periphery of the pile, using either access ducts or embedded strings of thermal sensors placed up to 500 mm apart. There are four levels of analysis for the measured temperature distribution, ranging from a basic qualitative review (assuming that a locally cooler zone hints at the existence of a nearby flaw) to higher levels that require the pile concreting record and sophisticated model analyses. In addition, the results on both extremities of the piles have to be mathematically adjusted to compensate for the roll-off (three-dimensional effects).

Proponents of the method claim that it can do all of the following (Piscsalko et al. 2016):

- Check the integrity of the whole pile volume, both inside and outside of the reinforcement cage and from head to tip
- Measure the thickness of the concrete cover
- Determine the centricity of the rebar cage
- Do all the above within a day or two from casting, thus saving precious construction time.

On the other hand, the thermal method has several inherent limitations:

- It can be performed during a rather limited time window - once a test is unsuccessful for any reason there is no option for a re-test.
- Due to the roll-off effects, the method may be only partially effective in the top and bottom parts of the pile, where most potential flaws are located.

- inclusions in the interior of the cage are difficult to detect by this method while a soft bottom condition is undetectable (Boeckmann and Loehr 2018).
- Reinforcing cage misalignment makes identification of concrete defects by thermal methods significantly more difficult (Boeckmann and Loehr 2018).
- Interpretation is not straightforward and may require supportive data: Cement type, concrete composition, construction records, soil profile, air temperature and groundwater level.
- Even if all the above data are available, expert analysis may take several days, thus cancelling the advantage of early testing.

2. FIELD TESTING

Since the main aim of the method is the discovery of flaws, research is necessary to establish its performance in terms of detection threshold or, in other words, the smallest flaw that it can positively detect under the worst-case scenario. This value is tightly woven with acceptance criteria that must relate to measurable data.

A number of researchers have explored the sensitivity of the method on bored piles with manufactured flaws, including sandbags (Mullins and Kranc (2007) and aggregates or blocks of cured low-strength concrete (Ashlock and Fotouhi 2014). The published results invariably are type C predictions (Lambe 1973) and the detection threshold found ranged between 8 and 15% of the pile's cross section (Schoehn et al. 2018).

In comparison, Becker et al. (2015) found no anomalies at all among 90 augered cast-in-place (CFA) small diameter piles with the thermal method. On another site, Bixler et al. (2016) found a single anomaly among 40 large diameter pile supporting a major bridge.

The detectability values that were obtained in controlled field testing may at best serve as a very rough guide for the following reasons:

- The number of defects available for testing on real piles is limited - usually not more than three defects per pile.
- The presented values disregard the 3D effect - a thin discontinuity may go unnoticed while a thicker one with the same cross section area will produce a clear thermal signature.
- The thermal sensors provide only discrete values, spaced vertically at 300 to 500 mm and almost one meter apart. A given flaw may either directly hit a sensor or miss it altogether.
- Both defects and sensors may have shifted during concreting.
- Flaws were invariably represented by thermally inert materials. Flaws of contaminated concrete (that is thermally active) were not investigated.
- The temperatures measured contain an unavoidable amount of noise or scatter that inhibits the identification of minor temperature anomalies.

The above considerations made us conclude that field testing is not the optimal tool and that the only way to perform a comprehensive and rigorous research on the capabilities of thermal testing is through digital modeling.

3. DIGITAL MODELING

3.1. Theoretical Background

When water is brought in contact with Portland cement it starts the chemical process of hydration - hardening accompanied by the emission of heat. The same goes for concrete in which cement is the active ingredient. This excess heat flows from the center of the pile outward into the ground surrounding the pile, which is usually cooler. Heat transfer in solids like concrete and soils follows Fourier's heat equation:

$$\frac{\partial \theta}{\partial t} = \frac{k}{\rho}\left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2}\right) + \frac{q}{\rho c} \qquad (1)$$

Where: θ- temperature, t - time, k - thermal conductivity, ρ - density, c - heat capacity, and q(t) - Rate of heat generation.

Where the surface of a warm solid is exposed to cooler air (or water), it emits heat by convection according to Newton's cooling law:

$$\frac{\partial Q}{\partial t} = hA(\theta_p - \theta_a) \qquad (2)$$

Where Q is the amount of heat lost, A is the interface area and θ_p, θ_a are the temperatures of the pile surface and the air or water, respectively. The factor h is defined as the heat transfer coefficient.

Analytical solutions of equation (1) are available for very simple situations. Asymmetrical, heterogeneous models require solutions by either Finite Elements (FE) or Finite Differences (FD) methods (Ballim and Graham 2004). www.piletest.com/thermaly, the model that we developed specifically for this purpose, is applicable to any three-dimensional foundation element, consisting of different materials with irregular geometry and arbitrary boundary conditions.

3.2. The Piletest thermal software "Thermaly"

As a software quality assurance step, we validated Thermaly against Ansys® (a leading FE software package) to calculate the temperature distribution in an infinite 1 m diameter cylinder during heating and cooling and obtained a perfect match (Fig. 1).

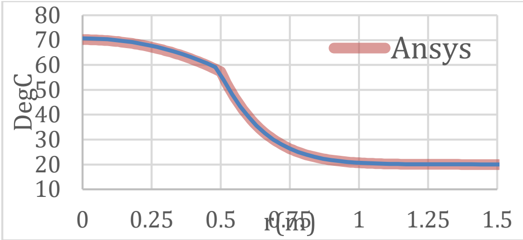

Fig 1. Comparison of Thermaly vs. Ansys® output.

In addition, we have compared the Thermaly output to the actual temperature measurement of a pile with fabricated flaws. Except for the flaw at 5m depth that may have shifted during concreting we found a good match (Fig. 2).

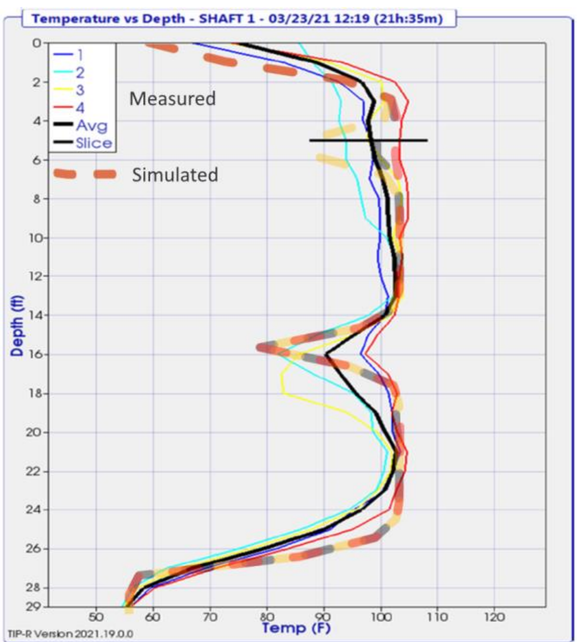

Fig 2. Simulated vs. measured results.

3.3. Typical thermal parameters

For site-specific analysis we recommend acquiring the parameters applicable to that site. Since for routine quality assurance (as opposed to research) this is highly impractical, parameters presented in literature (Oke 2002, Lee et al. 2009, Ballim and Graham 2004, Ge 2005) may be used as a starting point from which a sensitivity analysis can be performed.

3.4. Test scenarios

Within the scope of this study, we have investigated the following:

- Flaw composition: thermally inert and partially active.
- Flaw location and size: external, penetrating, total discontinuity.
- Boundary conditions: groundwater level, bottom of casing.

We modeled additional ones that are not report their results below due to lack of space. Our criterion for detectability was an anomaly of 5^0 F ($2.8\ ^0$C) that was suggested as the lowest discernible one (Mullins et al. 2009, Ashlock and Fotouhi 2014).

3.5. Flaw composition

All methods for pile integrity testing look for flaws, i.e. zones with abnormal properties. Soil pockets (that represented flaws in the above-mentioned in-situ tests) are thermally inert and as such the easiest to detect by the thermal method. Contaminated concrete, on the other hand, still produces heat due to the cement it contains. For example, contaminated concrete with an average cement content of 200 kg/m^3 (instead of a specified amount of 400 kg/m^3) will still emit 50% of the heat output of the surrounding concrete. However, its compressive strength may be reduced by 67% (Le Bow 2018) - clearly a defect. When looking for the worst-case scenario, therefore, our model should consider inclusions of contaminated concrete rather than clean sand or gravel.

3.6. External defects

The ability to identify defects outside the reinforcement cage (Fig. 3) is considered to be the foremost advantage of the thermal method over CSL (Boeckman and Loehr 2018). We, therefore, decided to run a series of simulations to check this claim.

Fig. 3. A pile with no concrete cover.

The embedded thermal sensors installed according to method B of ASTM (2014) form a rectangular grid attached to the inside of the rebar cage. The maximum spacing between the sensors is 1.0 m horizontally and 0.5 m vertically.

The results of a simulation on a 1.5m diameter pile with four thermal strings are presented in Fig. 4. An external flaw, 75 mm thick and 1.0 m tall, consisting of either dry or saturated sand and of varying widths was simulated. In the worst-case scenario (dry sand) the thermal effect is far smaller than the 5 F (2.8 K) threshold and even in the favorable case of saturated soil, the thermal effect is only evident at 80 degrees (1 m wide) opening.

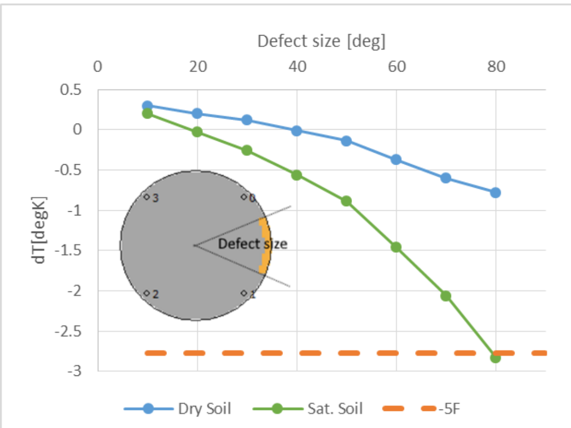

Fig. 4. Results for a defective cover

Evidently, the thermal method is unable to identify any significant flaw outside of the rebar cage.

3.7. Total discontinuity

We have checked the thermal effect at an age of 21 hrs. of a total discontinuity condition in a 1.5 m diameter pile in saturated sand with four thermal strings attached to the cage. Total discontinuities of various thicknesses and cement contents were modeled (Fig. 5). A vertical section of the flawed pile shows the heat distribution and how the major "cold" zone generated by a 120mm thick discontinuity is totally missed by the thermal nodes spaced 0.5m apart.

Fig 6 shows the relation between the discontinuity thickness, the degree of contamination (cement content), and the resulting temperature change. For example, a 200 mm thick discontinuity is undetectable unless its cement content is below 200 kg/m^3.

For small diameter (<600 mm diameter) piles, ASTM (2014) suggests testing with a single string, centrally located. We investigated this case for a complete discontinuity, with results similar to those found for the large diameter pile.

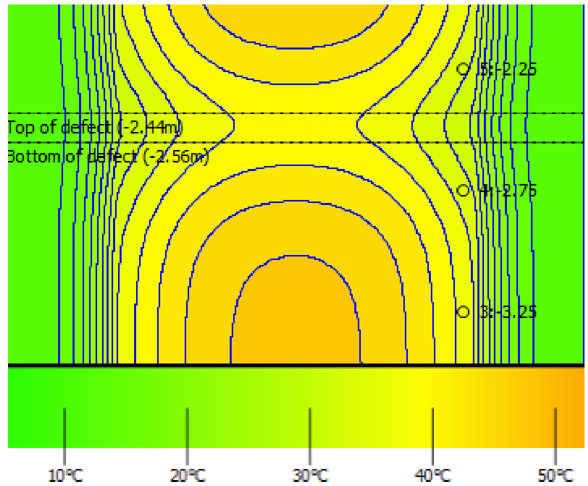

Fig. 5. A 120mm discontinuity temperature distribution (contours every 5 F).

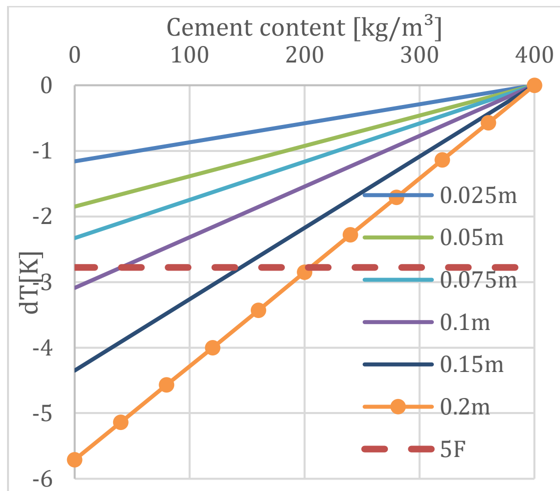

Fig. 6. Temperature anomaly vs cement content for total discontinuities of different thicknesses

3.7. Penetrating defects (Inclusions)

We have simulated a spherical flaw, penetrating the pile between two thermal nodes (Fig. 7), and plotted the flaw volume vs the resulting thermal anomaly at different cement contents. we found the detection threshold at 0.08 m^3 (80 liters) for inert material and 160 liters for a flaw with 50 % of the normal cement content (Fig. 8).

3.8. Groundwater and casing effect

Groundwater level (GWL, casing, and any sharp cross-section changes are typically generating a step-like anomaly in the thermal plot, potentially masking the thermal anomaly of a flaw. We ran a simulation of a 1m diameter pile, 6 m long. The soil is clean sand with GWL at 3 m depth. A total discontinuity, consisting of clean sand of various thicknesses, was simulated exactly above the GWL.

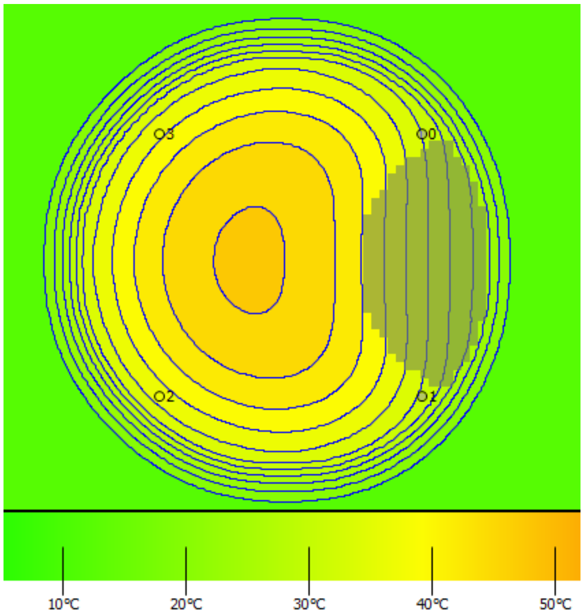

Fig. 7. A spherical penetrating flaw.

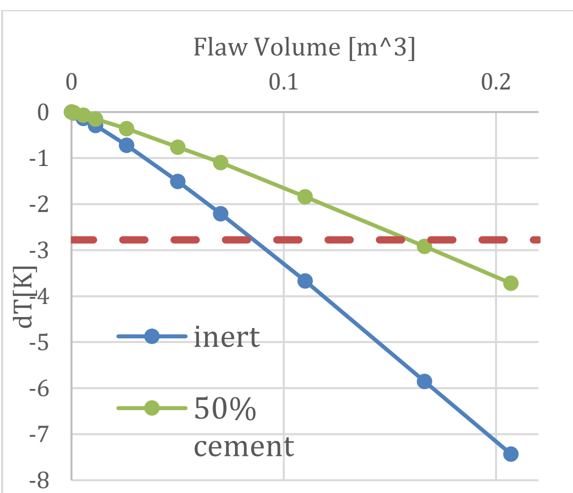

Fig. 8. Temperature anomaly vs cement content for penetrating flaws with different cement contents.

The results (Fig. 9) show that the significant thermal anomaly of the defect appears as an acceptable tolerance in GWL measurements and may hide flaws at this level.

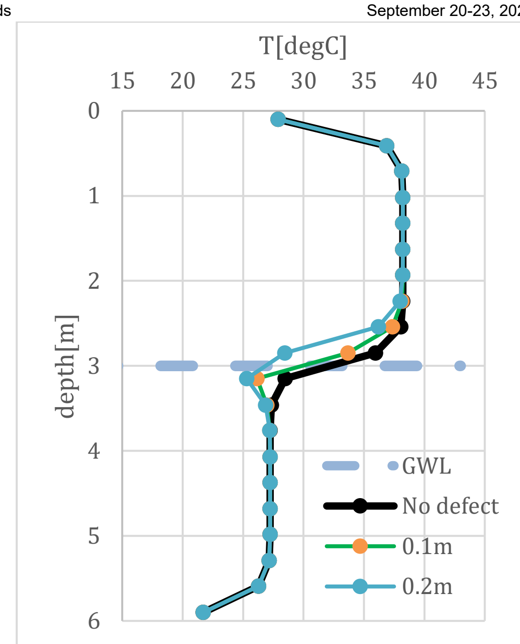

Fig. 9. A pile with a discontinuity of varying vertical size at groundwater level.

4. Conclusions/Recommendations

- Under worst-case scenarios, flaw detection thresholds of the thermal method are as follows:
    - Loss of cover: undetectable.
    - Penetrating flaw: from 80 liters (clean sand) up to 160 liters (contaminated concrete).
    - Total discontinuity: from 0.12 m (clean sand) to >0.2 m (contaminated concrete)
    - At GWL or casing bottom: >0.2 m (clean sand)
- The present use of widely spaced discrete sensors is a major drawback - it leads to unacceptably high detection thresholds thus resulting in multiple false negatives.
- Minimizing the spacing (probably by using fiber-optics) should lead to a meaningful improvement.
- Improved thermal methods will have to be validated by more type A predictions.
- Improved thermal methods will also require immediate interpretation techniques, accessible to practicing engineers.
- Numerical simulations are a powerful means to investigate the capabilities and shortcomings of thermal integrity testing.
- The above conclusions relate to the current standard (ASTM 2014) and may need to be revised whenever this standard will be materially revised.

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