INTEGRITY TESTING OF DIAPHRAGM WALLS BY THERMAL METHODS

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Abstract. Distributed measurements of temperature in drilled or bored pile foundations to assess the integrity of the curing concrete has become increasingly common in the past decade. These methods have the advantage of detecting significant anomalies inside and outside of the reinforcing cage as the initial hydrating of the cement in the concrete generates heat. Conditional acceptance or further review of the foundation can be obtained within one to two days of casting. More recently, these techniques have been applied to diaphragm wall panels used in tunnels and other building construction. The expected trends in the temperature versus depth data are reviewed, indicating the consistency of measurements on the wall faces and cooler zones at the corner. An example showing detection of local concrete cover changes and potential inclusions or non-uniformities at the bottom of the panels are also presented.

Keywords: Diaphragm Walls, Bored Piles, Thermal Integrity.

1 Introduction

Diaphragm walls or barrettes are common in the construction of tunnels, underground roadways and subways, residential and commercial buildings on tight urban sites and other excavations requiring unbraced support. When required by project specifications, integrity testing of diaphragm walls has been often performed by cross hole sonic logging [1], [2]. Over the last decade, integrity testing by thermal methods has become more common in shafts [3], [4]. This method uses the heat of hydration of the concrete to identify zones of lower or higher temperatures versus depth and quadrant of the circular pile foundation. Cooler zones indicate areas of lower cement content due to concrete batching errors, inclusions from surrounding soils or locally lower concrete volume. Hotter zones typically indicate the locations of overpour or higher concrete volume. Thermal integrity results are typically available once peak temperature in the shaft is reached, several hours or two to three days after casting.

Thermal methods on circular sections can also indicate shifting of the cage. A circular section is radially symmetric, and for a centered reinforcement cage with temperature measurements spaced equally around the cage, the measured temperatures will be very similar. If the cage shifts in the excavation, the portion of the cage that has moved closer to the soil will be cooler, while the diametrically opposite side will be closer to the pile center and therefore warmer. The average temperature in a vertically uniform shaft is unaffected by the shifted cage.

2 Modeling of Expected Heat Signatures in COMSOL

Thermal integrity measurements were modeled numerically in COMSOL, as has been previously described in detail for circular drilled bridge foundations [5]. Concrete hydration is modeled by an Arrhenius model that includes equivalent age and degree of hydration, parameters for which have also been separately investigated and calibrated for a number of concrete mix designs [6]. The heat generated by the curing concrete is transferred to the surrounding modeled soil by the general heat equation [5]. At the top of foundation element, a general heat flux surface simulates dissipation of heat in air. Table 1 describes the modelling parameters used to generate the model in this study.

Table 1. Modeling Parameters input into COMSOL for heat generation and transfer

Concrete Hydration Model Parameters		**Saturated Sand Model Parameters**	
E, Activation Energy	45991 J/mol	Thermal Conductivity	3 W/(m-K)
Beta, Hydration Shape Parameter	0.905	Density	1700 kg/m^3
Tau, Hydration Time Parameter	13.69 hours	Heat Capacity	800 J/kg/K
Au, Ultimate degree of hydration	0.689		
Hu, Heat of hydration of cementitious materials at 100% hydration	477 J/kg		
Initial Temperature	23 Deg C	Initial Temperature	22 Deg C
Wc, Weight of cement materials	614 kg/m^3		
Ww, Weight of water	267 kg/m^3		
Wca, Weight of course aggregate	802 kg/m^3		
Wfa, Weight of fine aggregate	547 kg/m^3		
Cc, Specific heat of cement	1000 J/kg/K		
Cw, Specific heat of water	4186 J/kg/K		
Cca, Specific heat of course aggregate	860 J/kg/K		
Cfa, Specific heat of fine aggregate	800 J/kg/K		

The predicted temperature profiles at locations on a rectangular reinforcing cage centered in a uniform rectangular wall with modeled dimensions of 6.4 m x 1.2 m x 32 m are shown in Figure 1. The four corners are cooler than temperatures modeled on the cage at the face because there is greater surface area to dissipate heat into the soil. Results from two locations on the face of the wall are plotted for clarity, but points calculated every meter from corner to corner along the wall face indicated the same temperature profile with depth. Also as expected, and similar to thermal integrity measurements in circular piles, heat is dissipated into the soil at the bottom of the wall, resulting in a characteristic roll off over the last two meters of the model. The top of this wall was modeled below the ground surface, and no reduction in temperature due to heat dissipation to the air is calculated.

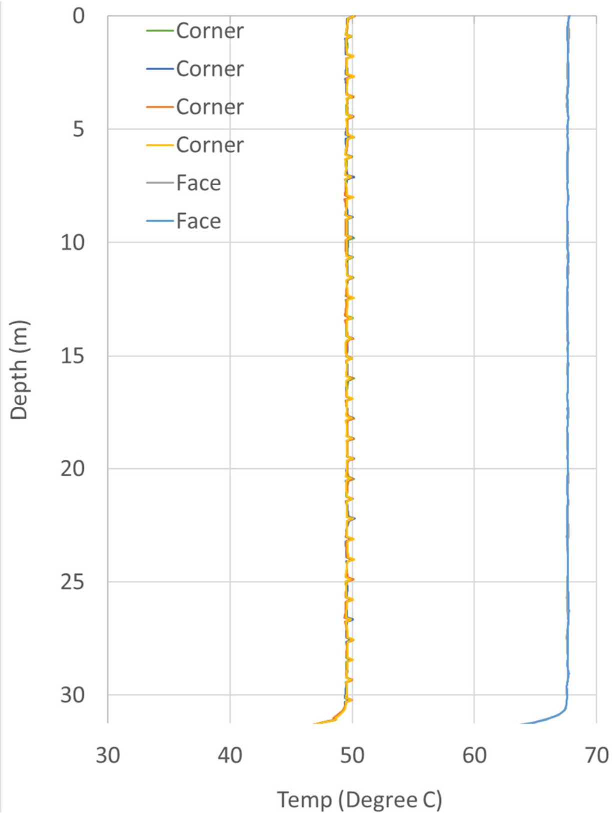

Fig. 1. COMSOL Thermal model results on the reinforcement cage at peak temperature for a uniform rectangular barrette.

3 Field Data

Twelve thermal wire cables® were attached to the reinforcement cage in a 6.4 by 1.2 by 32 meter long diaphragm wall panel. These cables have digital temperature sensors vertically separated by 300 mm and tied to longitudinal bars on the reinforcement cage. The cables are placed at each corner of the panel cage and spaced approximately 1 m apart as shown in the inset in Figure 2. The concrete mix design specifics and minerology was not made available, but was not the same as modeled in COMSOL. Therefore the magnitude of temperature is different between the model and the measurements.

Unlike the modeled results, the measured results indicate the cage is not exactly vertical over the long length of the pile. Reviewing the faces (left, Figure 2), the wires on the soil face (blue) are slightly cooler and therefore further from the center in the upper 10 m and from 20 m to the bottom. These same wires are slightly warmer than average and therefore closer to the center from 10 to 20 m below the top of concrete. The excavation face shows the opposite trend, and so the cage is curved slightly over the full excavation. The average temperature (black) from these eight wires indicates relative uniformity of the overall wall.

The corners (right, Figure 2) are cooler than the faces, as the modeled results also indicated. The average temperature (black) from the four corner wires over the entire 32 m length was constant and similar in shape, if not in magnitude, to the average from the faces. The consistent averages indicate consistent cross sectional areas of concrete along the length. The four profiles from the individual wires, however, are not all the same.

Below 30 m, initial inspection of wires 1 and 12 compared to 6 and 7 indicate a gradually decreasing temperature instead of more constant temperatures until the beginning of an abrupt, expected roll-off. The linear temperature reduction from 30 to 32 m is likely an inclusion or debris that has been displaced against the edge of the excavation, and is localized to that corner only. A similar trend is not observed in wires 2 and 11, also showing the limited extent of the temperature reduction.

Wires 1 and 12 also measured warmer temperatures than wires 6 and 7 in the upper 28 m, and then the pairs of curves invert below 28 m. This contrast between the two corner faces with the expected constant temperatures modeled from a uniform rectangular prism required further investigation.

As described above, when individual wires on a uniform cage deviate equally from the average, the normal interpretation is the cage has shifted if the wall is uniform with depth. The data from the corner wires, however, would indicate an abrupt bend in the cage at 28 m. Given the stiffness of this cage and the lack of reported installation problems, information on the means and methods of installation was requested instead.

Further details from the site indicated a 50 mm thick steel plate was placed to a depth of 28 m as a stopper on the corners containing wires 6 and 7. This reduced the concrete cover until the next panel was excavated and poured. Similarly, the corners containing wires 1 and 12 were cast after the stopper from the previous panel had been removed. The result was a rectangular prism to 28 m below top of concrete, followed by a rectanglular prism offset by 50 mm below 28 m. A rough sketch is included in the inset for Figure 3.

4 Revisiting Numerical Model with Field Geometry and Data

The COMSOL model was updated, keeping the temperature monitoring points on the cage the same, while shifting the curing concrete 50 mm over the last 4 m of the model. A 50 mm thick steel prism was added on the stopper side, although comparisons to a model with soil in this space were very similar. All other parameters of the model remained the same. The results of the modeling are presented in Figure 3.

Like the measured results, the temperature monitoring points in the model that were nearer the stopper were cooler in the upper 28 m, due to lower cover on the reinforcement cage. On the opposite side, the space vacated by the stopper from the previously cast adjacent panel was now filled with curing concrete, yielding higher temperatures. Below 28 m, where no stopper was placed between excavation and casting concrete, the modeled temperatures invert, also similar to the measured result.

5 Conclusions

Thermal integrity methods were modeled and implemented on a diaphragm wall project. The measurements on the wall faces and at the corners both indicated uniform cross sectional area, but noted discrepancies in the concrete cover, due either to movement of the cage in a constant section or due to differences in cover due to the installation technique. Further information from the site indicated changes in wall panel geometry with depth from the placement of a steel stopper. Subsequent modeling of the installed panel geometry matched the trend of the measurement.

Future efforts will include incorporating the volume of concrete placed in the wall excavation to calibrate changes more quantitatively in the wall dimensions and concrete cover at depth. Similarly, additional modelling in COMSOL could be performed with a less generic and more specific components of the in-place mix design to calibrate the cover changes to the measured data.

6 References

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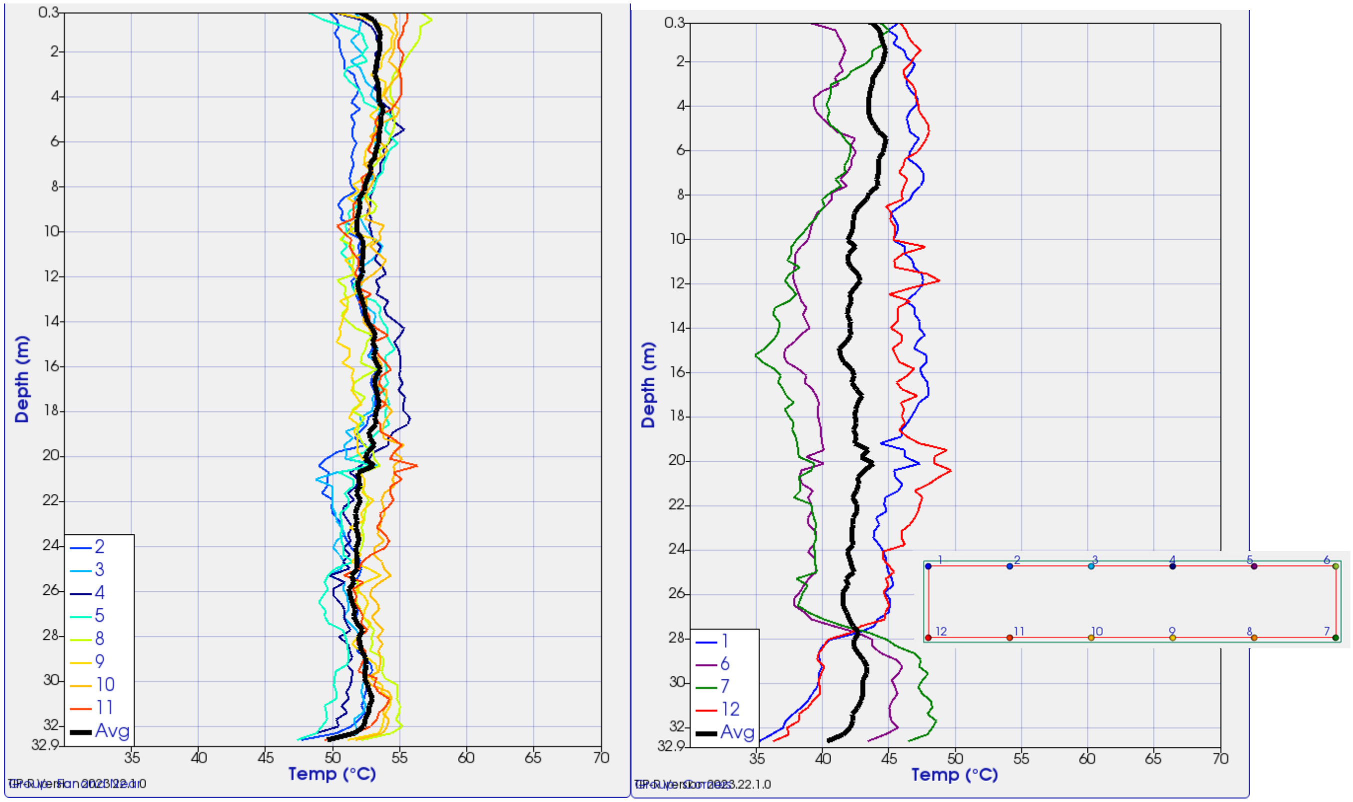

Fig. 2. Measurement results on cage faces (left) and corners (right) in barrette with stopper near wires 6 and 7. Stopper near corner wires 1 and 12 was removed prior to excavating and pouring current section

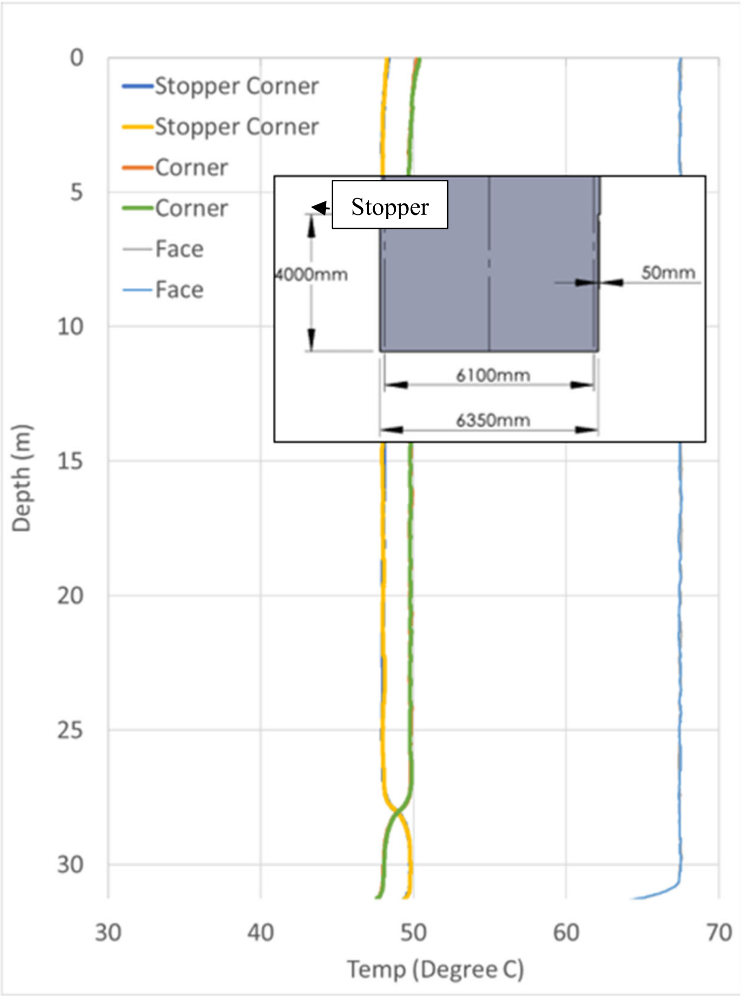

Fig. 3. COMSOL model results for the wall section dimensions (inset) over the bottom 4 m of the wall.