Thermal Integrity Profiling: An Innovative Technique for Drilled Shafts

SPECIAL ISSUE: INNOVATION

The durability of drilled shafts relies heavily on the thickness and quality of the concrete cover around the steel reinforcing cage. Until recently, this concrete cover went largely untested as non-destructive test methods could not test this region or were severely limited in the detection capability. Further, the concrete cover contributes significantly to the moment of inertia resisting bending moments (at least on the side in compression) and is imperative to proper rebar bond/development length. A relatively new test, known as Thermal Integrity Profiling (TIP), is capable of detecting the presence (or absence) of intact concrete both inside and outside the reinforcing cage, thus providing a 100% scan of the shaft.

The method was developed in the mid 1990s at the University of South Florida, Tampa, and has been used commercially since 2007. The test measures the internal temperature of the shaft, which is elevated by the cementitious materials present, and which react exothermically during hydration. The temperature rise from hydration energy has historically been considered an undesirable side effect that has been well studied in an effort to combat thermal-induced cracking. As high-strength concrete has been used more often, the associated higher cement content has caused higher internal temperature. As an example of this effect, Figure 1 shows the modeled core temperature versus time relationship for three, 6 ft (1.8 m) diameter shafts constructed with 2.7 ksi, 4.5 ksi, and 9 ksi (18.6 MPa, 31.0 MPa and 62.0 MPa) concrete with cement contents of 430, 600 and 860 lbs per cubic yard (255, 356 and 510 kg per m^3) of concrete, respectively. No flyash or slag was used in these example mixes.

The presence of flyash or slag in the mix design can drastically change the time to peak temperature (approximately 24 hrs in Figure 1) up to 50 or 60 hours. Retarders further delay the time to peak temperature. Thermal Integrity Profiling is intended to be performed near the peak temperature (after hydration has completed), but can be conducted several days afterward depending on shaft size and mix design. When considering the 4.5 ksi (31.0 MPa) shaft mix (Figure 1), 600 PCY or 356 kg/m^3), elevated shaft temperatures above 125ºF (52ºC) persist for 5 or 6 days. As a rule of thumb, TIP can be performed up to D days after concreting (where D is the shaft diameter in feet) and as early as 8 to 12 hours after concreting (depending upon shaft diameter and concrete mix), thus expediting the continuation of construction.

The internal temperature distribution within the shaft is bell shaped as shown in Figure 2. Larger diameter shafts develop the highest core temperatures but vary little as the shaft size exceeds 6 ft (1.8 m). Thermal Integrity Profiling measures the temperature at the radial location of the reinforcing cage where the gradient is highest. As a result, the measured temperature is highly sensitive to the cage alignment and subtle offsets are easily detected; in this case, a change of 3.5ºF (1.9ºC) equates to 1 in (25 mm) of cage offset. Therefore, when the cage is off center, measuring temperature at opposite sides of the cage are equally affected; one is hotter and the other is cooler. The average of both represents the temperature at the average location of the reinforcing cage. The individual temperature readings will indicate any cage eccentricity, but the average temperature will still allow for the determination of necks and bulges within the shaft. Note that the gradient for the various shaft sizes is similar at the location of the cage. This is dependent on the time of testing and mix design, but is affected very little by shaft diameter.

In this way, the local radius of the shaft is indicated by increases or decreases in temperature whereby the radius (or cover) is equally and oppositely higher or lower than that on the opposite side of the shaft when the cage is eccentric. As the gradient

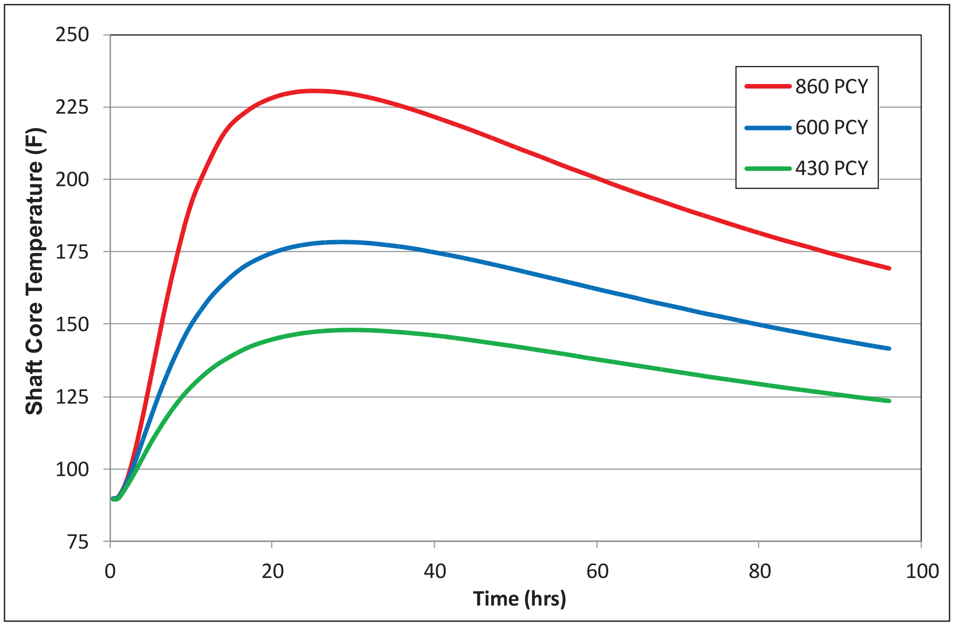

Figure 1. The effect of cement content on core temperature of a 6 ft (1.8 m) dia. shaft

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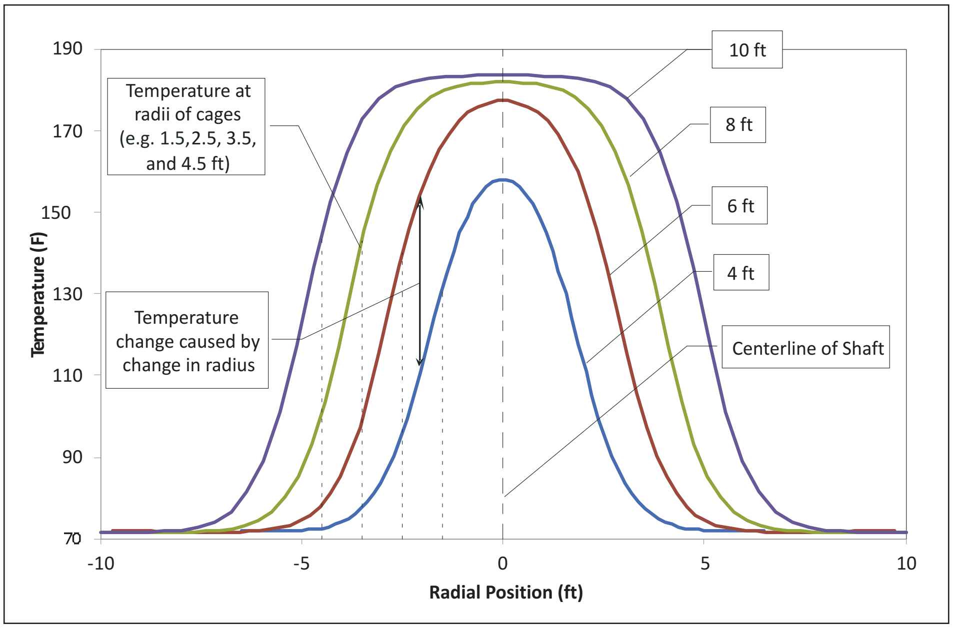

Figure 2. Knowledge of the normal temperature distribution is used to identify both cage alignment and local shaft radius (and cover)

is independent of shaft size, bulges or necks in the shaft are similarly detected as increases or decreases in the average temperature, respectively. The magnitude of a bulge (or neck) is computed using the same gradient that identifies cage offset. Remember, when the average temperature stays constant, the shaft diameter stays constant; changes in the average temperature are the easiest way to identify section changes.

Field Testing

Two approaches can be used to perform TIP: (1) use of a single thermal probe that is lowered into standard 1.5 in (38 mm) ID steel or plastic access tubes affixed to the reinforcing cage, like CSL, or (2) by installing into the cage multiple, a full length Thermal Wire either in lieu of or in conjunction with each access tube. The plurality of access tubes or Thermal Wires has most often been the same as CSL testing where one tube or Thermal Wire is used for every 1 ft (305 mm) of shaft diameter. For larger shafts, fewer tubes or Thermal Wires have been shown to be similarly effective.

Probe Option: When using access tubes, TIP is performed by lowering a thermal probe equipped with radially-oriented infrared sensors that record the internal wall temperature of the tubes in

Figure 3. Thermal probe system used to perform thermal integrity profiles (probe shown below)

four orthogonal directions. The measured temperatures and depth of the probe are monitored and recorded with a miniature computerized data acquisition system that plots the real-time progress for the operator to observe (Figure 3). One thermal profile is required from each tube, but often a second profile is obtained for data verification. The rate of descent is generally maintained at or below 0.5 ft/sec (0.15 m/sec) making the test duration around 7 minutes per 100 ft (30.5 m) of tube length (2 scans per tube).

TIP testing does not require water in the access tubes as testing is performed relatively quickly after concrete placement and the method is insensitive to de-bonding, allowing for the use of less costly PVC tubes; a cost savings to the project. If water has been introduced during construction for other integrity tests, it is removed, stored and returned after testing. Use of the same warm water prevents thermal shock to the tubes.

Thermal Wire Option: TIP can also be performed using an unmanned option where Thermal Wires are tied into the cage with discrete temperature sensors along its length. Each wire is connected to a dedicated data collection box secured somewhere near the top of the shaft. In this approach, data is continuously collected at user defined intervals (e.g., every 15 minutes) until the boxes are retrieved (Figure 4). This is convenient for scheduling testing personnel; no knowledge of the time to peak temperature is required. Rather, multiple tests are performed automatically and the optimal time of testing is selected from the library of recorded profiles. When used in conjunction with the probe option, pre-selected shafts can be periodically instrumented with Thermal Wires that both perform TIP tests and verify predictions of the temperature/time relationship. Shafts not pre-selected can be spot checked with the thermal probe when unforeseen mishaps occur. An additional Thermal Wire can be installed in the shaft with a known offset, typically 2 in (51 mm), from the reinforcing cage and the thermal gradient can be measured directly.

Figure 4. Thermal Wire system

Data Analysis

In general, two levels of analysis can be employed without using advanced numerical modeling. The first level makes observations of the raw thermal profiles, which with site experience, may provide enough insight into shaft acceptance. The second level of analysis superimposes construction logs and concrete placement information to both confirm first level observations and to convert temperature measurement into shaft shape (radius, cage alignment and concrete cover).

Level One Analysis: Direct observations of the temperature profiles quickly reveal potential bulges, necks, cage eccentricity, normal top and bottom of shaft as well as planned changes in section or soil strata. The top and bottom of the shaft dissipate internal temperature both longitudinally through the ends and radially out the sides. This causes a normal temperature profile to show a region approximately 1 diameter from the ends of the shaft where the temperature decreases with a somewhat circular shape (Figure 5). The average temperature from all tubes at a given depth provides an indication of shaft shape as radius and temperature form a strongly linear relationship in the region of the cage (see Figure 2). Tube numbering is sequentially clockwise looking down on the top of shaft where tube 1 is the northern most tube.

Using direct observations, measurements from tubes on opposite sides are higher or lower than the average, but the average forms a relatively straight line down to a depth of 25 ft (7.6 m). The straight upper portion of the average temperature indicates a constant cylindrically-shaped shaft. The variations between tubes is relatively constant indicating the cage is straight but eccentric a constant amount. From 25 to 35 ft (7.6 to 10.7 m), a bulge in the shaft is indicated by the higher temperature in that region which is more to one side (tubes 3, 4 and 5). Competent bearing materials were encountered at 35 ft (7.6 m) which reduces auger wobble/walk, and a slightly reduced temperature is noted which accounts for a diameter closer to the auger dimension.

Level Two Analysis: When superimposing known construction information, much of the level one observations can be confirmed: (1) Top of shaft corresponds to the discontinuity in the temperature profile at the ground surface; from 0 to 4 ft (0 to 1.2 m) the measurements are from an exposed tube in air. (2) The bottom of permanent casing at 20 ft (6.1 m) corresponds to the linear average temperature measurements, however the soil appears to have been stabile even deeper. (3) The bulge corresponds to a notable change in the slope of the concrete yield plot. (4) The bottom of shaft elevation confirms the normal bottom of shaft temperature profile where the tubes terminate approximately 6 in (152 mm) from the bottom of the excavation. If the tubes are permitted to touch the bottom of the excavation, the bottom of the shaft profile would look similar to the reverse of the shaft top. If the tubes are terminated too far above the bottom of excavation, the normal decrease in temperature would not be apparent.

Finally, the concrete placement logs can be converted to average radius of concrete placed from each truck based on the yield plot data (Figure 6). When compared to the average temperature profile the slope of the temperature/radius gradient can be determined and used to establish the effective shaft radius and cover (Figure 7).

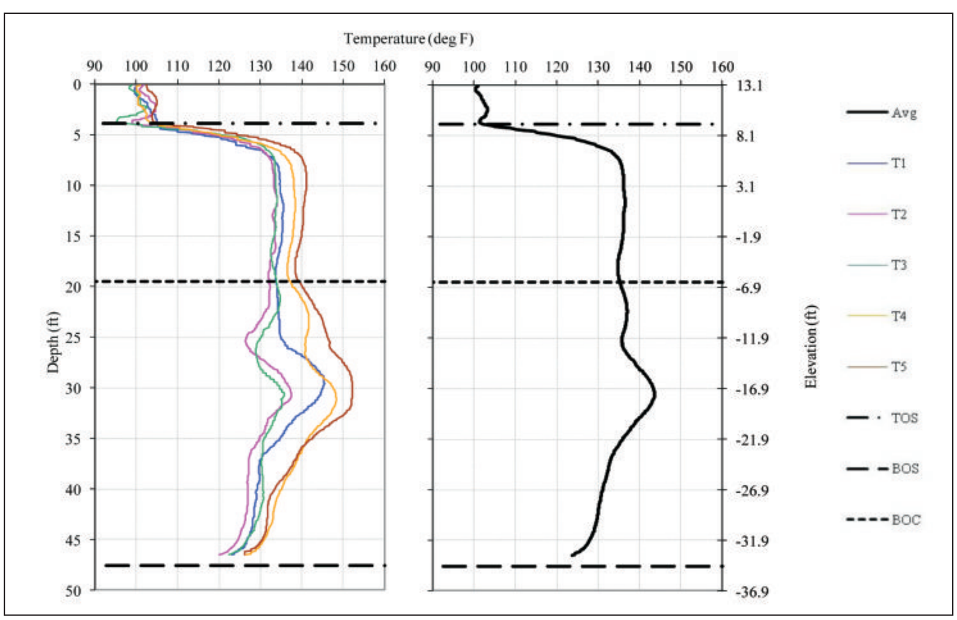

Figure 5.Thermal profile of 54-in-dia. shaft with available construction information

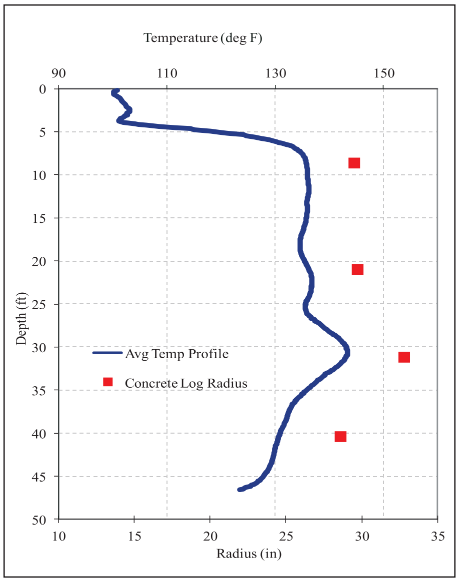

Figure 6. Correlation between concrete placement logs and average temperature profile

Like most other integrity assessment methods, local measurements are compared to the rest of that tube (or tube pair). In the case of TIP, local temperature measurements are compared to the rest of the shaft. This gives rise to the term effective shaft radius, which refers to the radius of intact concrete (of average quality relative to the rest of the shaft) that would produce the measured temperature. In cases of poorer quality or contaminated concrete a reduced temperature will result from the same amount of concrete as indicated in Figure 1 from three shafts with different cement contents.

Finally, using thermal dissipation theory for material boundaries, the end effects from bimodal temperature dissipation can be removed to show the shaft shape without end effects (Figure 7). Depending on the user, this step may not be needed, or even wanted, as the presence of the normal temperature decrease near the end is evidence of proper cage proximity to the bottom of the excavation. However, allowing the end effects to be corrected is an effective tool for determining problems near the shaft top and bottom. Data from two shafts on the same site with the end corrections implemented (Figure 8) shows that one shaft has a serious problem at the toe while the other shaft corrects nicely.

Summary

Unlike above-ground concrete structures, drilled shafts rely on effective post construction evaluation via non-destructive testing methods. The capabilities of Thermal Integrity Profiling include means to assess concrete quality, reinforcing cage alignment, shaft radius and concrete cover. The TIP test further allows for accelerated construction as this test will be completed with minimal wait time (typically within 24 hours of concreting) while all other non-destructive test methods require wait times after concreting of 3 to 7 days minimum. Perhaps most significant, the concrete outside the reinforcing cage can now be more thoroughly reviewed. Previously used integrity methods have been historically unable to ascertain the complete concrete cover with several widely used methods unable to provide any information regarding concrete cover.

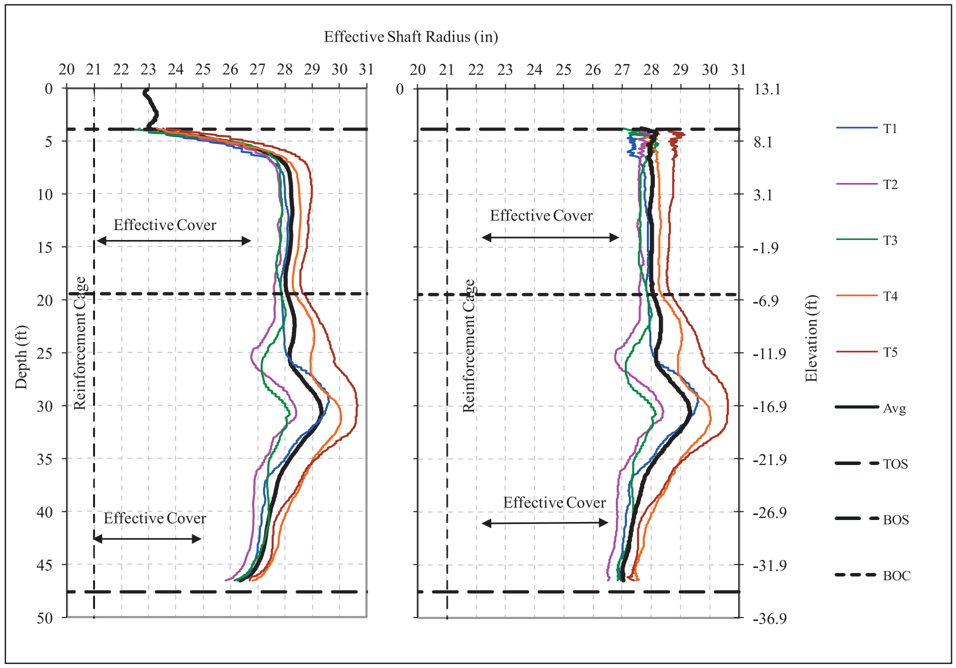

Figure 7. Temperature profiles converted to effective radius with and without end effects (left and right respectively)

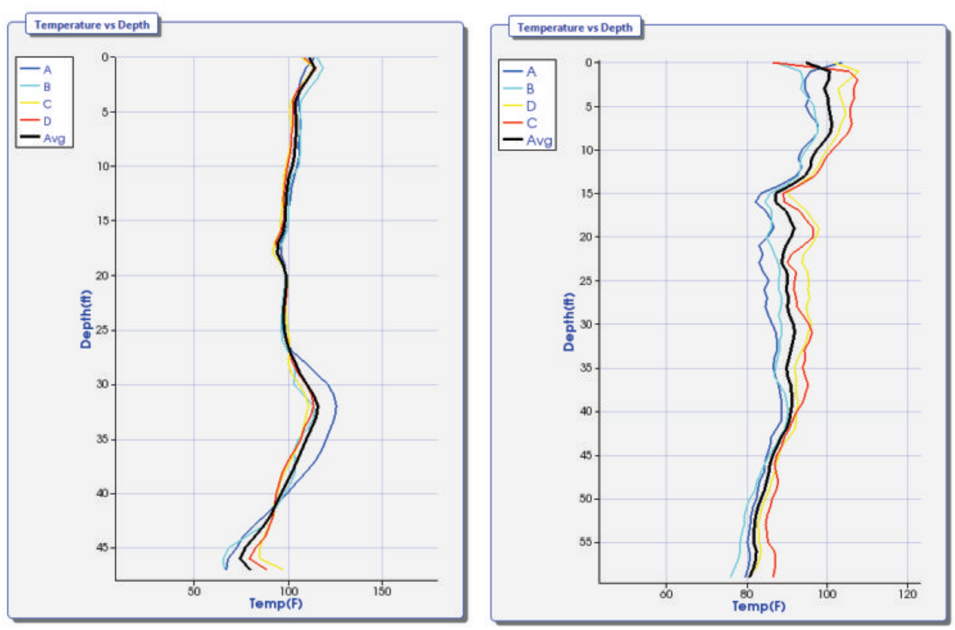

Figure 8. Thermal data showing corrections for end effects reveals a problem at the shaft bottom for the shaft shown on left