Non-Destructive Testing of Drilled Shafts – Current Practice and New Method

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ABSTRACT:

Quality control of drilled shafts is greatly dependent upon the practices of the site personnel. In many applications it is difficult or even not possible to fully inspect the shaft prior to concreting, such as when the shaft is drilled under slurry. There are numerous methods currently available to assess the integrity of drilled shafts. This paper will compare evaluations by three existing methods with a new method of Thermal Integrity Profiling for assessing integrity.

Introduction

Drilled shafts can be the chosen foundation element in many applications due to the large axial and lateral capacities attainable for very large drilled shafts. Drilled shafts can be cast in a dry hole which allows for inspection of the hole prior to casting. However, unstable soil conditions frequently require drilled shafts to be cast under slurry as a means to stabilize the surrounding soils during the construction process. When casting a drilled shaft under slurry, it is very difficult to impossible to accurately and efficiently inspect the hole prior to casting concrete and it is equally difficult to inspect the shaft during the casting process. Many of the above mentioned processes are blind to inspection and therefore the chances increase for having defects present in the completed elements.

There are several methods available for integrity testing completed elements. Each of these methods has advantages and limitations with no one method yielding perfect testing of the entire element. Some test methods can test the integrity within a small proximity of an access tube while others will test the shaft core but do not test the areas outside the reinforcing cage (concrete cover). A new integrity testing method has recently emerged which is based upon patented research conducted by Professor Gray Mullins with the University of South Florida (Mullins, 2004). This new method involves measuring the heat generated in the concrete element during the hydration process.

This Thermal Integrity Profiling (TIP) method has the ability to evaluate the entire cross-section of the element under test, along the entire shaft length, allowing for verification of concrete cover while also evaluating the core of the shaft. Pile length to diameter ratios which can restrict some other integrity testing methods (such as low strain integrity testing) are not a restriction to the TIP method. Additionally, the TIP method is not limited by large non-uniform cross section changes that can occur by design or unintentionally during the construction process. Test shafts with purposely built defects located both outside the reinforcing cage as well as within the reinforcing cage have been constructed and the defects have been easily determined from the TIP test (Mullins, 2010). This paper will discuss the current state-of-practice for integrity testing of drilled shafts and will detail this new TIP method. An example will be included showing the TIP method in practice.

Current Shaft Integrity Testing methods

Typical integrity test methods currently being utilized for drilled shafts include the low strain pile integrity test and the cross-hole ultrasonic test. The gamma logging test is another available method, but is not as widely used as the low strain integrity test or cross-hole sonic logging (CSL). The low strain pile integrity test method involves attaching an accelerometer to the pile top (typically using a thin layer of wax or putty) and striking the pile top surface with a small handheld hammer. The hammer strike creates a compressive wave within the pile which will reflect off the pile toe and return to the pile top. The motion of the impact and return signals are measured by an accelerometer. Changes in the pile cross-section (necking or bulging) will also cause a reflection which will be measured by the accelerometer at a time earlier than the expected pile toe reflection. This low strain integrity test will reveal major defects within a pile. This test is useful in that it is very fast and economical, requiring no special construction techniques (no access tubes required, etc.) other than a prepared flat top surface to attach the accelerometer. One individual can test any or all piles on a site. Non-uniformities will cause reflections which can complicate data interpretation. Bulges located near the pile top create multiple reflections which can make it difficult to assess the integrity of the shaft below this point. As the length to diameter ratio increases beyond approximately 20 to 50 (depending on pile uniformity and soil strength), it can be difficult to get a reflection from the pile toe thus leaving the lower section of the pile potentially unevaluated. Additionally, any reinforcing rods extending significantly above the pile top can cause vibrations which create difficulty in interpretation.

The Cross-Hole Sonic Logging test requires access tubes placed into the shaft prior to casting. If the access tubes are not available, the test can’t be conducted. For the Cross-Hole Sonic Logging (CSL) test, steel or plastic pipes with a typical 1.5 to 2 inch (38 to 51mm) diameter are cast into the shaft. These access tubes are immediately filled with water upon completion of the shaft. For CSL testing, steel access pipes are preferred since they do not typically de-bond from the concrete as can happen with plastic access pipes.

The CSL test entails inserting an ultrasonic transmitter into one access tube and a receiver into another access tube for a particular shaft. The transmitter and receiver are lowered and/or raised at a constant rate while usually keeping the transmitter and receiver parallel to one another. The transmit frequencies are typically 40 KHz to 70 KHz. Knowing the tube spacing, the arrival times for the received signals can be converted to wavespeed (when tube spacings are measured at the surface and assumed to be constant throughout the length of the shaft). Additionally, the received signal strength can be an indication of concrete quality. The CSL test is limited in that it only provides an indication of concrete quality between the access tubes which are usually located on the inside of the reinforcing cage. Scanning all access tube combinations will give a fairly accurate assessment of the pile core but the CSL test cannot assess the concrete outside the access tubes. Thus the concrete cover cannot be determined with the CSL method.

The CSL access tubes can also be used to perform a gamma-gamma logging (GGL) test. In this GGL test, a probe typically containing cesium-137 (a radioactive material) is lowered into the CSL access tube. The GGL probe will emit particles which are captured by the concrete and backscattered to a photon counter which relates to the density of the adjacent material through which the particles passed. This test can scan in 360 degrees around the access tubes so there is some testing of the concrete outside the reinforcing cage, but the sensing range is practically limited to perhaps 3 inches (76 mm) as the energy is halved every two inches (51 mm). This test will scan less than 20 percent of the pile cross-section in all cases. For large diameter shafts, this test will scan less than 10 percent of pile cross-section (figure 1).

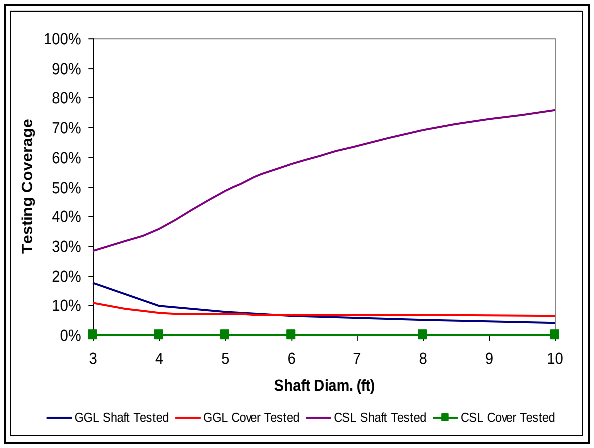

Figure 1

Each of the above mentioned test methods can be successfully used to help determine the integrity of drilled shafts, but each test method also has associated limitations. The Thermal Integrity Profiler (TIP) is a new method that has the ability to overcome many of the limitations these other test methods exhibit.

Thermal Integrity Profile

The Thermal Integrity Profile (TIP) method determines the integrity of a shaft both inside and outside the reinforcing cage by measuring the temperature of the concrete hydration along the length of the shaft. The temperature measurements are made by either passing a thermal probe through a de-watered access tube (Mullins, 2004) or from embedding thermal cables (Piscsalko, 2013) within the shaft. At each depth all temperature readings are averaged together and, along with the total volume data, used to determine the overall shape of the shaft as a function of depth.

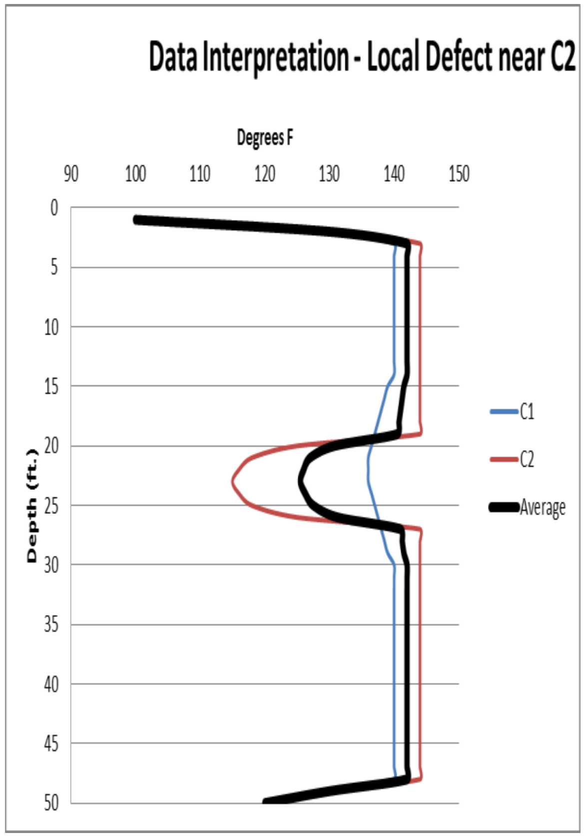

Figure 2

Curing concrete exhibits a normal heat signature dependent upon the shaft diameter, concrete mix design, concrete quality, and soil conditions. Insufficient cement content (defect) will cause a local reduction in temperature near the defect. For smaller diameter shafts, the defect may also produce a smaller reduction in temperature even diagonally opposite the defect. Any temperature measurements which are cooler than the overall average are areas of reduced concrete volume (defect) or poor concrete quality and any area with a higher temperature than the average are areas of increased concrete volume (bulge). Figure 2 shows measurements for a small diameter shaft which would indicate a defect located closer to location C2 in this example (the normal temperature signature is reduced more at measurement location C2 as compared with measurement location C1).

In addition to determining concrete integrity, the TIP test will also reveal any potential issues with reinforcing cage alignment by comparing TIP measurements from radially opposite locations versus the average value. If the first location is cooler or warmer than the average and the radially opposite location behaves in an opposite manner then the cage is not concentric with the shaft. For example, if measurement location one is warmer than the average this indicates that this location is closer to the center, while measurement location two is cooler than the average this indicates that this location is closer to the surrounding soil.

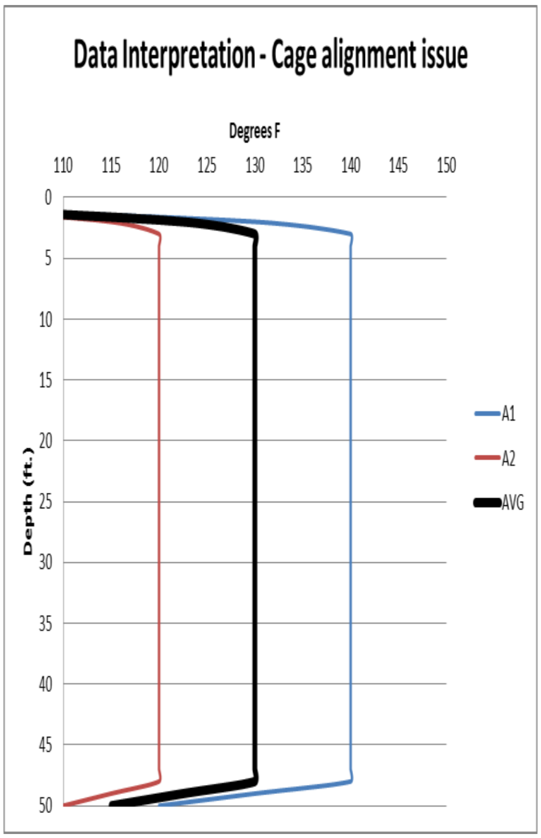

Figure 3

When considering both these measurements together, it can be determined that the cage has shifted such that location A1 is closer to the shaft center and location A2 is closer to the surrounding soil (figure 3). This gives additional information on concrete cover. There is reduced concrete cover at location A2.

The recommended number of measuring locations (e.g. access tubes or thermal wires) is one per foot of shaft diameter (e.g. 10 thermal cables installed for a 10 foot diameter shaft) and spaced approximately equally around the reinforcing cage perimeter. It is recommended that an even number of tubes or wires be installed, with pairs being placed diametrically opposite one another to enable lateral movement, if any, of the reinforcing cage to be easily determined. The thermal integrity profiler will then easily scan the complete shaft cross-section and any anomalies greater than or equal to 10% of the cross-sectional area will be detected by multiple measuring locations. Anomalies smaller than 10% of cross-sectional area will be detected by the thermal integrity profiler at the nearest measuring location, but these small anomalies are often typically insignificant in the performance of the shaft.

Generally heat transfer away from the shaft is only radial along the length of the pile shaft. However at the top and bottom of the shaft the heat transfer is both radial and longitudinal and thus the temperatures typically reduce at the two ends of the shaft. This top and bottom of shaft temperature reduction roll-off typically seen in a thermal integrity profile has a hyperbolic tangent shape. Knowing this characteristic roll-off shape allows for correction to be applied to the thermal measurements at the top and bottom of the shaft. When the correction is applied to the shaft top and bottom, the roll off portions of the curve are corrected to match the interior measurements (curves generally flatten out). Once the top and bottom of the curves have been adjusted, the analysis in these areas is similar to the remainder of the measurements.

The TIP measurements using a thermal probe require that CSL-type access tubes be installed in the shaft. These tubes can be steel or plastic. The test will be performed typically 18 to 48 hours after completion of the shaft. The optimum time is dependent upon the shaft diameter and mix design. Large diameter shafts or concrete mix designs that are high in slag will take a longer time to reach peak temperature. The measurement is made by first de-watering the first access tube (water should be stored in a thermal container if CSL testing is to be later performed). The probe is then warmed in this water to allow the probe to come to the approximate temperature of the shaft. Next the probe is lowered into the access tube at a rate of no more than 0.3 ft/sec, recording all temperatures from four infra-red temperature sensors located at every 90^0 radially around the probe. When the first tube is completed, the water from tube two is transferred to tube one and the thermal measurement is taken in tube two. This is continued around the shaft until all tube measurements have been completed. Once the final tube has been thermally tested, the water removed from tube one is replaced in the final access tube. There are no de-bonding concerns related to de-watering steel tubes since the coefficients of thermal expansion for steel and concrete are nearly identical. If no CSL testing will be conducted, the tubes are not required to be water filled.

An alternate method for measuring the concrete temperatures during the hydration process is to embed thermal cables into the shaft. These cables have temperature sensors placed every foot vertically and are placed adjacent to or instead of the probe access tubes (typically one thermal cable per foot of shaft diameter, spaced approximately equal around the reinforcing cage perimeter). The thermal cables are simply tied to the vertical rebar members of the reinforcing cage. The thermal measurements are taken automatically at regular time intervals (usually approximately every 15 minutes) at least until the shaft has reached its peak temperature.

One additional thermal cable can be installed in a radial direction with a known and fixed horizontal distance (typically 2- 3 inches (51 – 76 mm)) from another thermal cable. These two adjacent thermal measurements can determine the thermal gradient of this shaft. This temperature gradient at the outer portions of a shaft is approximately linear and can be directly applied to individual temperature measurements to help evaluate the effective shaft radius (knowing the temperature change over a known distance and understanding that this temperature signature is linear near the shaft perimeter allows direct application of this measured gradient to all temperature measurements).

When any individual temperature measurement is lower than the average, the loss of cover can be calculated using the measured temperature gradient. Similarly, when any temperature measurement is higher than the average, the increase in cover can be determined using the measured temperature gradient. Using the concrete volume installation records and the total measured concrete volume, the overall average temperature is correlated to the average radius. Once this average temperature to average radius correlation has been established, the radius at any point along the shaft can be directly calculated.

If radially opposite locations in a shaft show one side being warmer than the average while the opposite side is cooler than average, we can use the temperature to radius conversion or the measured temperature gradient to determine the lateral distance of cage movement.

Thermal Example

In this example, a 66 inch (1700 mm) diameter by 179.5 foot (54.2m) long drilled shaft was installed with six plastic CSL access tubes and six thermal wires located near these access tubes. The cage was built with two 100 foot (30.2m) sections which were field spliced over the hole. The installed concrete, converted to effective radius, as manually logged by the onsite Inspector is shown in figure 4.

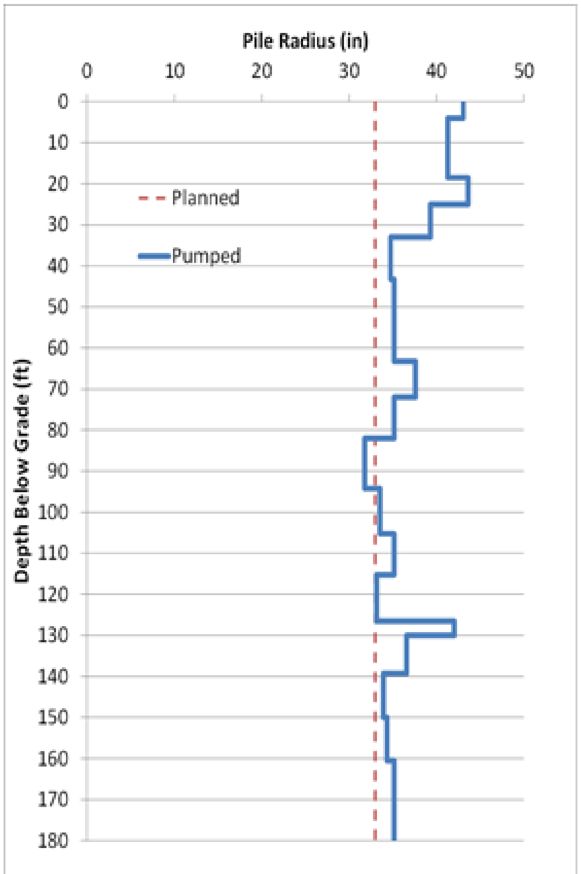

Figure 4

The total volume installed was 191 yds^3 (146 m^3). This volume yields an overall average shaft radius of 36.3 inches (922mm). The volume versus depth log indicates that the shaft radius is generally greater than the design radius throughout the shaft. The bulge located at approximately 130 ft (40m) depth was caused by over-pumping at this depth to keep the tremie pipe free, and was due to delays from problems at the batch plant. The upper 28 feet (8.5m) is oversized because an 84 inch (2130mm) diameter temporary casing was installed to a depth covering the upper 28 feet (8.5m). This is all clearly shown in figure 4.

The drilled shaft was instrumented with six thermal cables. The cables were attached to the top and bottom reinforcing cage sections and spliced together over the hole. The thermal cable splice connection used to attach the upper and lower section cables was a simple plug together underwater connector that required minimal effort to mate. The raw thermal data from this test is shown in figure 5. The thermal data shows no major defects but does indicate that the cage is slightly misaligned from the shaft top down to a depth of approximately 70 feet (21m) (wire 2, 3, and 4 are cooler than average while their diametrically opposite wires 1, 5, 6 are similarly warmer than average). Additionally, the oversized shaft diameter in the upper 28 feet (8.5m) is quite obvious as the average temperature is significantly increased over this portion of the shaft.

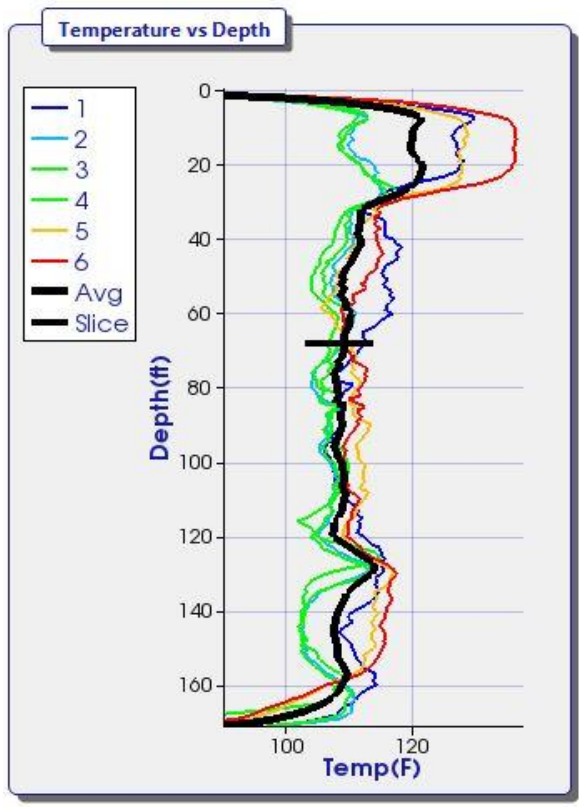

Figure 5

At the shaft bottom, a normal one diameter roll-off in the temperature data is observed for thermal cables 1, 2, and 3. The thermal cables 4, 5, and 6 however indicate that there is an abnormal roll off in the temperature data at the shaft bottom, indicating a soft bottom in this quadrant of the shaft. This soft bottom extends from approximately 155 feet (47m) depth to the shaft bottom (54.2m).

Figure 6 shows the thermal data after the conversion from temperature to effective shaft radius and correction for the hyperbolic temperature roll-off. The top and bottom roll-off shown in figure 5 are corrected in figure 6 by applying a hyperbolic tangent curve to these portions of the thermal data. The data clearly shows that the 33 inch (838) design radius is achieved throughout the shaft. Additionally, the average thermal radius curve has a shape that is very similar to the radius curve developed from the pumping data recorded during installation (figure 4).

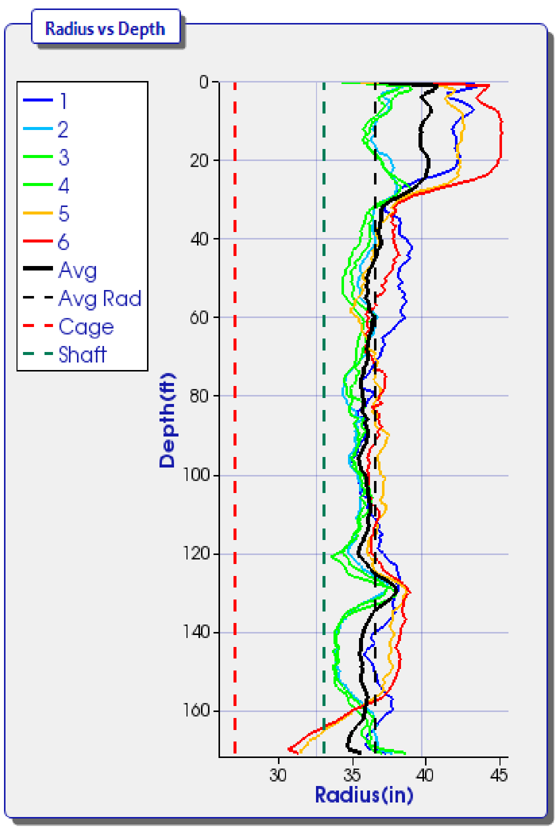

Figure 6

The radius shows a slight increase at a depth of approximately 130 feet (40m) due to the excessive pumping in this location and the upper portion shows a greatly increased radius where the larger temporary casing was installed (42 inch or 1065 mm OD radius for temporary casing). Looking closer at the individual thermal wire data near the shaft top, it shows that the oversized radius is much greater at thermal cable locations 1, 5, and 6. Thermal cable locations 2, 3, and 4 all show a slight increase in radius in the upper portion of the shaft, but this increased radius is not nearly as significant as the other thermal cable locations, indicating that the increased radius in the upper portion of the shaft is biased in the direction of thermal cable 1, 5, and 6 locations. This clearly shows the temporary casing is not centered on the cage.

Knowing the total volume pumped into the shaft, a 3-dimension drawing of the shaft is created in figure 7. In this view it is quite simple to quickly see all the major details of the shaft including the bulge in the upper portion, slight bulge at approximately 130 feet (40m) , and the reduced concrete cover on one side of the shaft bottom.

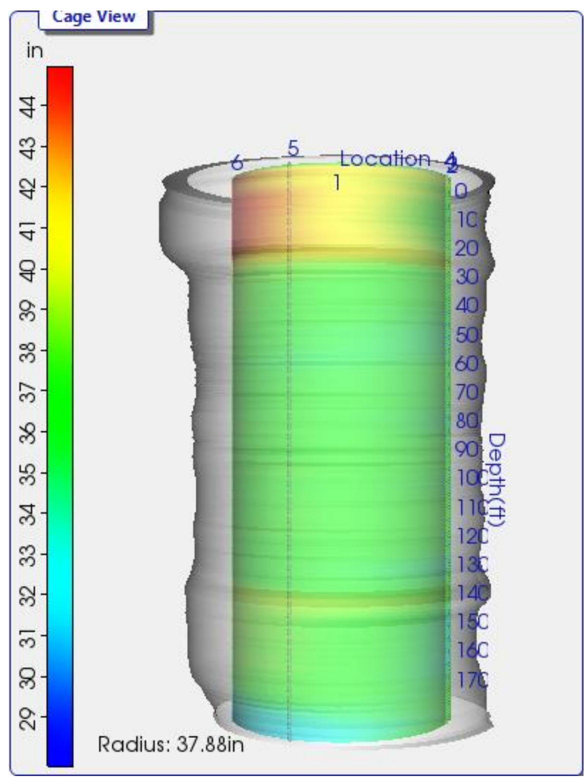

Figure 7

The upper 15 ft. (4.6m) portion of this shaft was later excavated (figure 8) and it is clearly shown that the bulge in the upper portion of the shaft is indeed where the thermal testing had predicted, and that the casing is not concentric with the concrete. The radius for the excavated shaft was measured at the location of the upper bulge and matched the predicted radius from thermal profiling.

Figure 8

The CSL records for this same shaft indicate that there are no problems in any tube scan combinations. Figure 9 shows a typical CSL result. All scan combinations look similar. The CSL test offers no indication of the concrete cover or cage alignment but simply that the integrity of the shaft central core section.

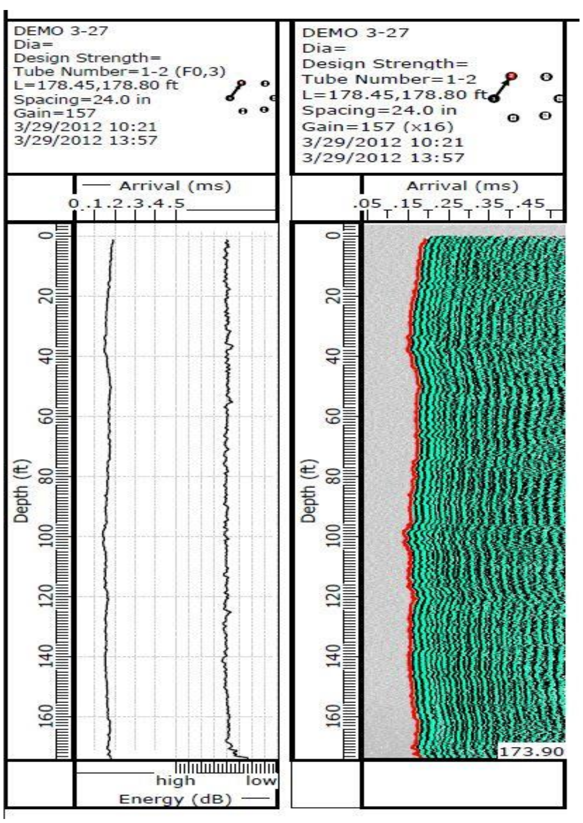

Figure 9

The CSL test results do not indicate the bulge in the upper portion of the shaft, the nonconcentric reinforcing cage (particularly for the top cased section), or a reduced concrete cover around the southwest portion of the shaft toe. CSL only evaluated the concrete located between tube locations and was incapable of determining shaft integrity outside the reinforcing cage.

Conclusions

The general trend has been an increase in the use of drilled shafts. These drilled shafts are often installed with little or no knowledge of the final shaft integrity, particularly for shafts installed under slurry conditions. Current non-destructive test methods can each provide partial information as to shaft integrity, but each method also has limitations which do not provide evaluation of the entire shaft cross-section.

The Thermal Integrity Profile method measures the shaft temperature during the hydration process to make an assessment of the shaft integrity. From these temperature measurements, the effective shaft radius can be determined. The TIP method allows for assessment of the full shaft cross-section both inside and outside the cage, and for the full length, which no other single current method can provide. Additionally, the cage alignment can be determined and the concrete cover evaluated from the TIP data. Since the TIP test is dependent upon the concrete hydration, this results in the TIP test being conducted approximately 24 hours after the shaft has been cast, which is a major advantage over current methods as this can potentially accelerate the construction process.

Many field tests have been successfully conducted and comparisons made with other available methods. The TIP test provides an overall look at the shaft based upon the local heat signature. Unlike current test methods, the TIP method provides the shaft integrity without the limitations associated with other methods, including overall shape of the shaft, concrete cover over entire cross-section, and cage alignment.

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