State of Practice and Advances in Quality Control Methods for Drilled Shafts

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ABSTRACT

Drilled shafts are increasingly selected for deep foundation support. To satisfy the design intent, the as-built shaft shape, shaft vertical alignment, shaft base cleanliness, cage alignment, concrete cover, and concrete integrity are all important. Several quality control methods are available to check these design considerations. Many current quality control test methods are time consuming, don't provide quantitative information, don't address all design considerations, or cannot be performed until the shaft has cured for several days. There have been several recent advances in drilled shaft quality control instrumentation. These recent advances in drilled shaft quality control methods offer owners, engineers, and contractors innovative and powerful tools for quality control and quality assurance of drilled shafts. This paper addresses recent advances in quality control methods for drilled shafts and presents field data from recent projects where these technologies have been used for evaluation.

INTRODUCTION

Drilled shafts are increasingly being selected as a deep foundation support element due to the large axial and lateral capacities that can be attained. When cast in a dry hole, the drilled shaft excavation can be inspected prior to casting the shaft, but the casting process is still difficult to inspect with any accuracy. Soil conditions often dictate that the drilled shafts be wet cast under slurry to stabilize the surrounding soils during the shaft construction process. When casting under slurry, it is very difficult to nearly impossible to inspect the hole prior to casting and it is equally difficult to inspect the shaft during the casting process. Considering that the wet cast installations are done with no direct inspection ability, the drilled shaft integrity is often unknown, which increases risk to the process.

In wet cast installations, the shaft sidewalls are frequently profiled to determine the shaft shape from the excavated area as well as shaft verticality. Most traditional sidewall profiling devices are time consuming and lack sufficient resolution. The Shaft Area Profile Evaluator (SHAPE) is a new device used for profiling the sidewalls in a wet cast drilled shaft using high frequency ultrasonic pulses. The device is quickly deployed by connecting directly to the drilling stem or

Kelly bar where it is then lowered to the shaft base. Advancement rate is approximately 1 foot per second, allowing a shaft to be quickly profiled.

Drilled shaft bottoms are frequently checked prior to concrete placement to determine debris layer thickness and base cleanliness. Traditional test methods for measuring debris thickness are time intensive and subjective to the viewer, with no quantitative results. The Shaft Quantitative Inspection Device (SQUID) is a device used for measuring the extent of the debris layer at the base of a drilled shaft. The device measures the force on three penetrometers as a function of the displacement measured from independent displacement sensing plates. This device is quickly deployed by connecting directly to the drilling stem or Kelly bar where it is then lowered to the shaft bottom. Quick deployment and the ability to view real-time results allows for the test be completed in approximately 15 minutes. The resulting force versus displacement information gives the designers and engineers a quantitative measure of the debris thickness at the shaft base.

Thermal Integrity Profiling (TIP) is a non-destructive testing technology that utilizes the temperature generated by curing cement (hydration energy) to assess the quality of cast in place concrete foundations. Thermal integrity results are best analyzed between 50% of peak temperature to peak temperature. Depending on the shaft size, peak temperature generally occurs 18 to 24 hours after placement. Compared to traditional integrity test methods, Thermal Integrity Profiling greatly shortens the time window from shaft construction to shaft acceptance. The temperature measurements, along with placed volume and installation details, are used to model the effective shaft radius, shaft shape, and concrete coverage beyond the reinforcing cage. The alignment of reinforcing cage can also be evaluated. The addition of cloud based communication from the field data logging equipment to the test consultant further accelerates the testing process as real-time data can be viewed from anywhere in the world.

To satisfy the design intent, the as-built shaft shape, vertical alignment, base cleanliness, reinforcing cage alignment, concrete cover, and shaft integrity are all important to evaluate. There are several quality control methods and devices used to evaluate many of these design considerations. Many current quality control test methods have significant limitations associated with these various methods. This paper will discuss several quality control inspection methods and techniques and detail new state of practice quality control methods for drilled shafts.

DRILLED SHAFT INTEGRITY TESTING METHODS

Integrity testing methods frequently used for drilled shafts include low strain pile integrity testing (pulse-echo or transient response method), crosshole sonic logging, gamma-gamma logging, and thermal integrity profiling. These test methods have advantages and limitations with the simplest test methods which require no preplanning or material cast into the shaft having the greatest limitations. The other methods can overcome some or all of the limitations of the more simplistic methods as well as better identify and quantify any anomalous zones. A brief summary of the commonly used integrity testing methods is presented in Table 1.

Table 1. Overview of Commonly Used Integrity Testing Methods						
Method	ASTM Standard	Time Required Between Shaft Casting and Testing	Requires Material to be Cast in Shaft	Cross Section Evaluated	Advantages	Limitations
Pulse Echo (PEM)	D 5882	No sooner than 7 days after casting or after the concrete achieves at least 75% of its design strength*	No	Only major cross sectional changes	• Quick • Economical	• Depth often limited to 30 or 40 shaft diameters
Transient Response (TRM)	D 5882	No sooner than 7 days after casting or after the concrete achieves at least 75% of its design strength*	No	Only major cross sectional changes	• Quick • Economical	• Depth often limited to 30 or 40 shaft
Crosshole Sonic Logging (CSL)	D 6760	No sooner than 3 to 7 days. Larger diameter shafts closer to 7 days*	Yes, one steel or PVC access tube per 305 mm (12 in) of shaft diameter	Cross sectional area delineated by perimeter of access tubes	• Widely available integrity test • Depth limited only by probe cable length	• Sensitive to access tube/concrete bond • Fine horizontal cracks unlikely to be detected • Depth limited only by cable length
Gamma-Gamma Logging (GGL)	None	No time restriction. Test can be performed immediately after concrete placement.	Yes, one PVC access tube per 305 mm (12 in) of shaft diameter	Cross sectional area extending 102 mm (4 in) from center of access tube	• Concrete cover evaluated in vicinity of access tubes	• Storage and transport of gamma source • Depth limited only by probe cable length
Thermal Integrity Profiling (TIP)	D 7949	12 to 48 hours depending on shaft diameter	Yes, one thermal wire or one access tube (thermal probe method) per 305 mm (12 in) of shaft diameter	Full shaft cross sectional area	• Assesses cage alignment • Evaluates concrete cover	• Fine horizontal cracks unlikely to be detected • Depth limited only by thermal wire or probe cable length

* - per ASTM standard

Advances in Integrity Testing

The most recent advance in drilled shaft integrity testing uses the hydration temperature of the shaft concrete to assess concrete integrity as well as reinforcing cage alignment, and concrete cover. The Thermal Integrity Profiling (TIP) method uses Thermal Wire® cables that are attached to the reinforcing cage prior to casting the shaft. The thermal wires have temperature sensors evenly typically spaced every 305 mm (12 inches) along the length of each wire. One thermal wire is installed for each 305 mm (12 inches) of drilled shaft diameter, evenly spaced around the reinforcing cage and rounded to the nearest whole number. The thermal wires begin collecting data immediately after the shaft is cast. Procedures for performing the test are further described in ASTM standard D7949. Figure 1 presents a photograph of the thermal wire cables extending above the top of a concreted shaft with the end of each cable attached to a data logger.

Figure 1. Thermal wire cables attached to data loggers

Drilled shafts have a heat signature which is directly related to the cement content in the mix design. The concrete volume and concrete quality are both directly related to the cement content. The TIP method measures the elevated temperatures during the hydration process to assess the shaft integrity and concrete quality. The temperature measurements are automatically taken, typically every 15 minutes beginning just after casting and continuing until the concrete reaches its peak temperature, which typically occurs within 24 to 48 hours after casting. These measurements can be downloaded by on-site personnel and sent to the engineer for analysis. In many cases, the measurements can be automatically transmitted from the site to a cloud server. The data can be remotely monitored and data analysis and reporting can begin as soon as the appropriate analysis time is reached. Data transfer using the cloud server reduces data collection costs as well as accelerates data analysis and reporting.

The temperature of each sensor on each wire is scanned for local reductions in temperature. This results in a temperature versus depth profile as illustrated in Figure 2 (left). The local temperature reduction near 27.4 m (90 feet) indicates a local defect or poor-quality concrete. Defects are best observed during the early curing stage, at a time when the shaft temperature is one half the peak temperature.

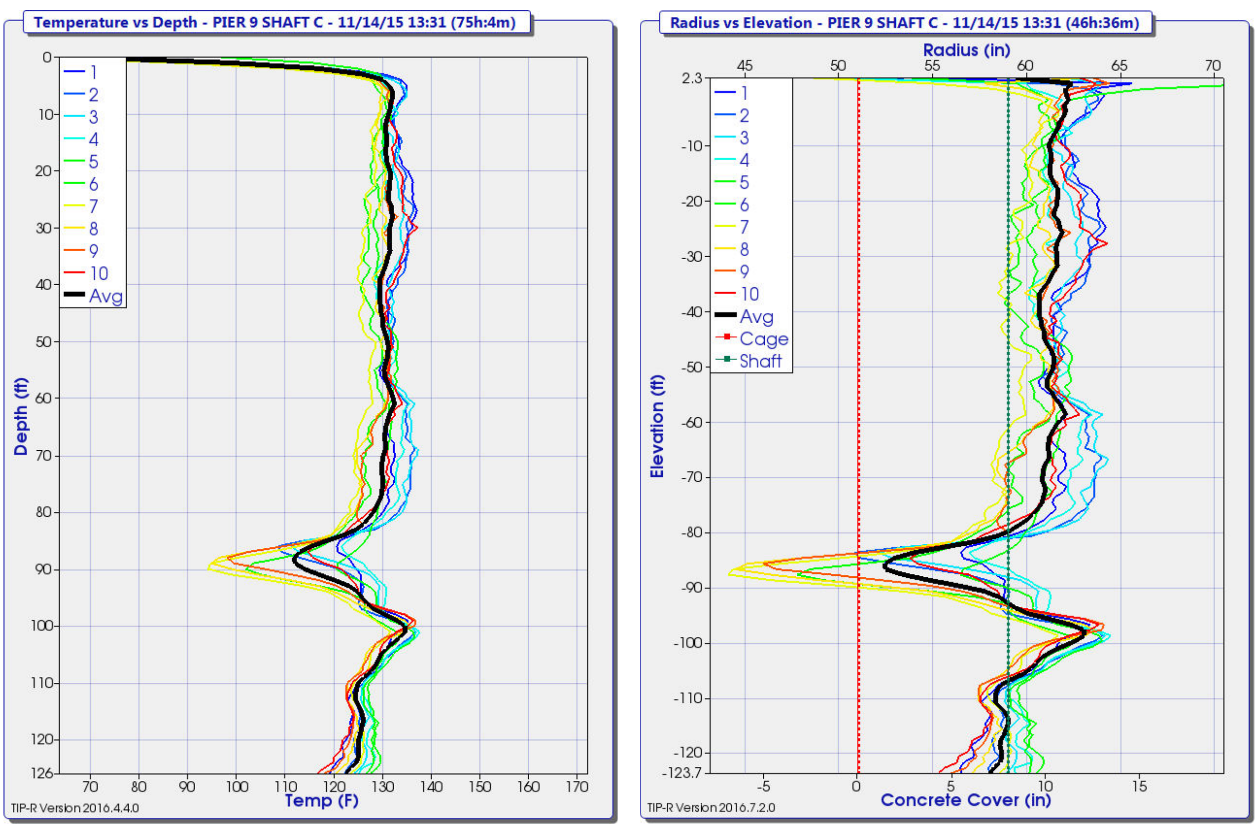

Figure 2. Thermal results of temperature vs depth (left) and radius vs elevation (right) for the same drilled shaft with a defect at 27.4 m (90 ft.)

A local reduction in cement content in the concrete (defect) will interrupt the normal temperature signature in the area of the defect. This defect may also be seen in adjacent measurement locations if the defect is severe. The severe local reduction in temperature at 27.4 m (90 feet) in indicates a defect at this location which was confirmed by coring the shaft.

The average recorded temperature is related to the average radius based on the placed concrete volume. Once this average temperature to average radius relationship has been established, all local temperature readings can be converted to local effective radii. This allows the effective shaft radius to be depicted along the length of the shaft. Figure 2 (right) presents a plot of the effective shaft radius versus elevation. When the individual temperature measurement is lower than the overall average temperature, a local reduction in radius (concrete cover) is indicated. Figure 2 (right) also includes the concrete cover versus elevation from the local reduction in radius. When an individual temperature measurement is higher than the overall average temperature, a local increase (bulge) in radius is indicated.

Along with determining shaft integrity, the thermal integrity profiling method can also detect any eccentricities in the reinforcing cage. When comparing temperature measurements from diametrically opposite locations versus the average temperature value, the cage alignment can be determined. If one temperature measurement location is cooler than the average temperature at this elevation and the diametrically opposite temperature measurement location is warmer than average temperature at the same elevation, this indicates that the cage is not centered. The cooler than average measurements indicate a reinforcing cage shifted towards the soil interface while the warmer than average measurements indicate a location shifted towards the shaft center.

The ability to determine cage eccentricity provides additional information on concrete cover, which can be reduced even without having a defect present. In the example shown in Figure 3, temperature measurement location 5A is warmer than the overall average temperature throughout the length of the shaft while diametrically opposite location 1A is cooler than the overall average temperature, so it can be determined that the cage is shifted such that location 5A is closer to the shaft center and location 1A is closer to the surrounding soil indicating a reduction of concrete cover at location 1A.

The thermal integrity profiling method provides the advantage of assessing the entire cross-section of the shaft, including the area outside the reinforcing cage, which may be critical for performance under lateral loading. The test can also be completed soon after the shaft is cast, allowing the construction process to proceed at an accelerated pace.

Since the thermal integrity method uses the heat generated by the hydration of the cement, pre-planning is required to install the wires prior to placement and obtain thermal data immediately after the shaft is cast. Thermal integrity profiling using thermal wires cannot be performed if the thermal wires are not installed in the shaft during the construction process. Thermal integrity profiling can be performed using thermal probes that are lowered into dewatered access tubes if access tubes were cast in a shaft. However, in the thermal probe method, temperature data is only collected at the time of testing. Hence, when using thermal probes, it may be necessary to be on-site multiple times or at non-standard work hours or work days to collect data at the key analysis time. The access tubes in long shafts can also be difficult to dewater thus complicating testing using the thermal probe method.

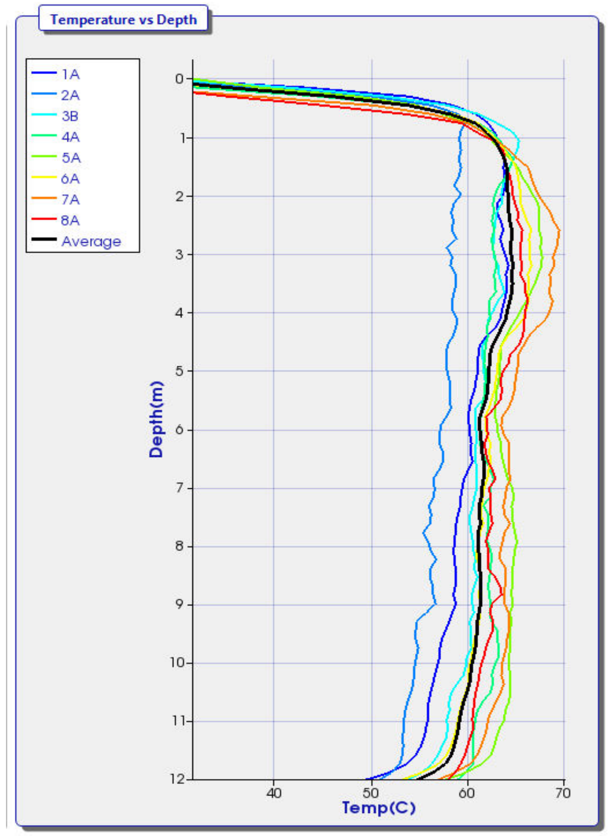

Figure 3. Thermal results showing cage eccentricity

SHAFT BASE CLEANLINESS EVALUATION METHODS

The bases of drilled shafts are often checked prior to concrete placement to evaluate the extent of debris at the shaft bottom. This is particularly true of wet cast drilled shafts where the base condition cannot be visually observed. According to Brown et al., (2010), many project owners limit the average debris or sediment thickness at the base to 25 mm (0.5 inches) and the maximum to 37.5 mm (1.5 inches) for shafts that rely on end bearing for a large portion of their geotechnical resistance. Shaft base cleanliness is very important for these end bearing shafts as well as to minimize concrete contamination from debris during the concrete pour.

Traditionally, shaft base cleanliness has been evaluated using a weighed tape or with a Shaft Inspection Device (SID) or its successor the Mini-SID, both of which are video camera based systems housed within a diving bell type device. A new quantitative means of evaluating base cleanliness, the Shaft Quantitative Inspection Device or SQUID uses force penetrometers and displacement plates to determine debris thickness. A brief summary of the more commonly used shaft base cleanliness evaluation methods as well as their advantages and their limitations is presented in Table 2.

Table 2. Overview of Commonly Used Base Cleanliness Evaluation Methods					
Method	ASTM Standard	Description of Device	Debris Determination	Advantages	Limitations
Weighted Tape	None	Heavy weights attached to the end of a hand held measuring tape	Highly subjective based on immediate stoppage or slow sink rate of weighed tape on bottom	•Quick •Economical	•Subjective •Not quantitative •Accuracy
Mini-SID	None	Waterproof camera mounted inside of a dewatered diving bell type device attached to a cable and winch. Pressurized gas is used to displace drilling slurry for observation of base material.	Debris thickness determined by camera observation of debris adjacent to colored pins at 12.5, 25, and 37.5 mm (0.5, 1.0, and 1.5 in) height above diving bell base.	•Quantifiable debris thickness •Photograph of base material	•Speed and ease of use •Quantitative determination tied to visual scaling
SQUID	None	Three force penetrometers and three displacement measurement plates attached to a Kelly bar lowered collection device	Debris thickness determined by penetrometer force and displacement measurement	•Speed and ease of use •Highly quantitative •3 measurement points per test	•No photograph of base material

Advances in Base Cleanliness Evaluation Methods

The most recent advance in drilled shaft base cleanliness assessments is the SQUID device that quickly provides quantitative measurements at the base on a drilled shaft. The device consists of three cone penetrometers and three displacement plates. The device measures the force independently on each of three instrumented penetrometers as they are advanced through the soil at the shaft base. The displacement is measured using three independent contact plates that remain in contact with the top of the debris layer while the penetrometers move through the debris layer and into the bearing material. As shown in Figure 4, test results are presented graphically as a force vs. displacement plot as well as in table form with the numeric value for the debris thickness at each penetrometer location.

The device quickly pins to the Kelly bar that not only allows the test to be done quickly but also allows the drilling rig to provide the force required to penetrate harder materials at the shaft base. After the device is pinned to the Kelly bar, the typical total time required to complete the standard base cleanliness evaluation tests at the shaft center and at the four orthogonal sides is on the order of 15 to 30 minutes. The speed of testing is particularly attractive in materials such as shale that can degrade in strength over time.

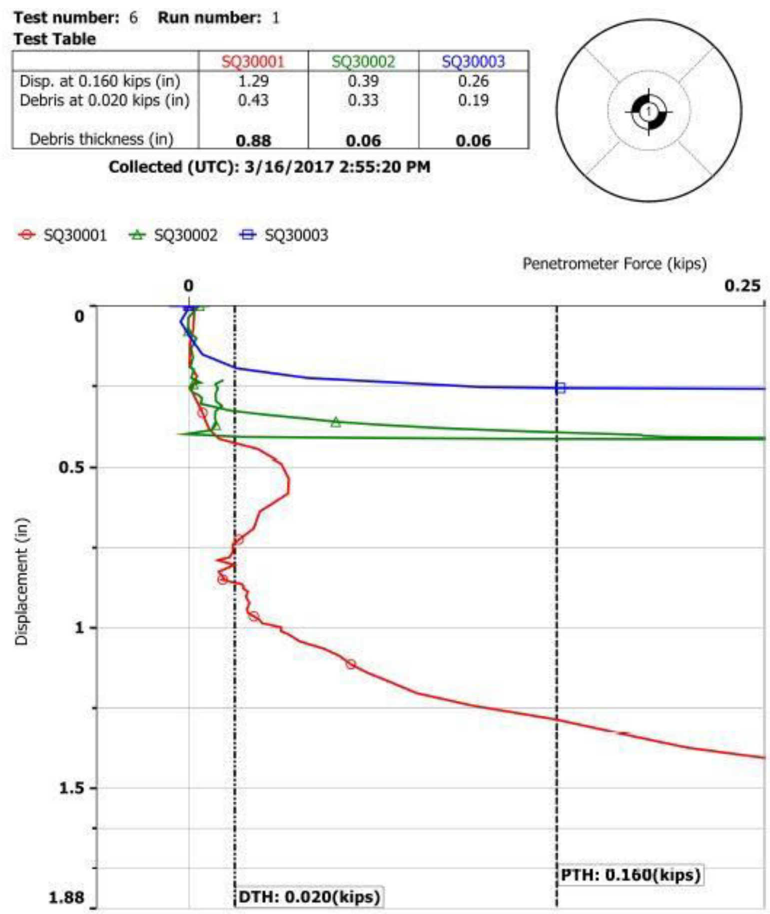

Figure 4. Force vs. displacement plot with debris thickness determination from SQUID test

SHAFT SHAPE EVALUATION METHODS

Drilled shaft shape and the resulting inferred cross sectional area is increasingly being checked for design compliance. Concrete volume plots of the concrete volume placed versus elevation have historically been used to identify enlarged areas where concrete may be filling voids as well as areas of concern where the concrete volume placed is less than anticipated. In wet cast installations, shaft sidewalls have been profiled using both mechanical calipers and ultra-sonic profiling devices to determine the shaft shape from the excavated area as well as shaft verticality. These sidewall profiling devices are however relatively time consuming, have safety concerns since the equipment must be set up over an open excavation, and, depending on the device, may lack sufficient resolution. A brief summary of the more commonly used shaft shape and verticality evaluation methods as well as their advantages and their limitations is presented in Table 3.

Table 3. Overview of Commonly Used Shaft Shape and Verticality Evaluation Methods

Method	ASTM Standard	Description of Device	Shaft Shape Determination	Advantages	Limitations
Concrete Volume Plots	None	Weighted tape used to determine top of concrete relative to placed concrete volume.	Crude geometry assessment obtained from simple construction observations	•Economical	•Verticality cannot be evaluated •Subjective shape •Not quantitative •Requires personnel near open excavation
Mechanical Calipers	None	Typically four spring-loaded arms “feel” the shaft sidewall as the device is raised.	Shaft geometry determined from diameter measurements on 90 degree axis	•Quantitative measurement	•Speed and ease of use •Safety working over or near open excavation
Ultra-sonic Calipers	None	Ultra-sonic signals are transmitted and received as the device is lowered and/or raised in shaft excavation.	Depending on device, the shaft geometry and verticality determined from discrete ultrasonic signals on 90 degree axis or 360 degree scan (when rotated)	•360 degree scan at selected depths available from one device. •Quantitative to highly quantitative depending on device.	•Speed •Safety working over open hole
Shaft Area Profile Evaluator	None	Calibrated ultra-sonic signals are transmitted and received as the device is lowered on Kelly bar at 305 mm / sec (1 foot / sec)	Shaft geometry and verticality determined from continuously emitted ultra-sonic signals on 45 degree axis.	•Speed •Safety •Self-calibrating versus depth •Highly quantitative	•Eight sensor (45 degree axis) sidewall scan

Advances in Shaft Shape and Verticality Determination Methods

The most recent advance in drilled shaft shape and verticality determination methods is the Shaft Area Profile Evaluator or SHAPE. The device quickly attaches to the drill stem and can collect data while advancing down the excavation at comparatively high rates of speed. This greatly reduces the time required to profile the shaft sidewalls and allow the concreting to begin in a much shorter time than previously possible. The device simultaneously transmits and receives ultra-sonic signals from eight individual sensors mounted 45 degrees apart. This allows the device to advance downhole at a rate of up to 305 mm/sec (1 feet/sec). The device also requires no cables for data transmission thereby keeping personnel away from the open excavation during the test. The eight sensors and frequency of the transmitted and received signals allow the device to acquire a highly quantitative shaft shape without stopping or rotating the device.

An integrated self-calibrating feature automatically adjusts for changes in wave speed if the slurry should be denser with depth, greatly improving the accuracy of the computed radii. The device quickly determines the various radii along the length of the shaft as well as the verticality of the shaft. A representative axis scan is presented in Figure 5.

The test is very easily and quickly accomplished with a simple pin attachment to the drilling stem. The speed and accuracy that the shaft sidewall and verticality can be determined and reported allows the drilled shaft verification process to proceed efficiently. This allows the excavated shaft to be concreted quickly further improving the quality of the drilled shaft.

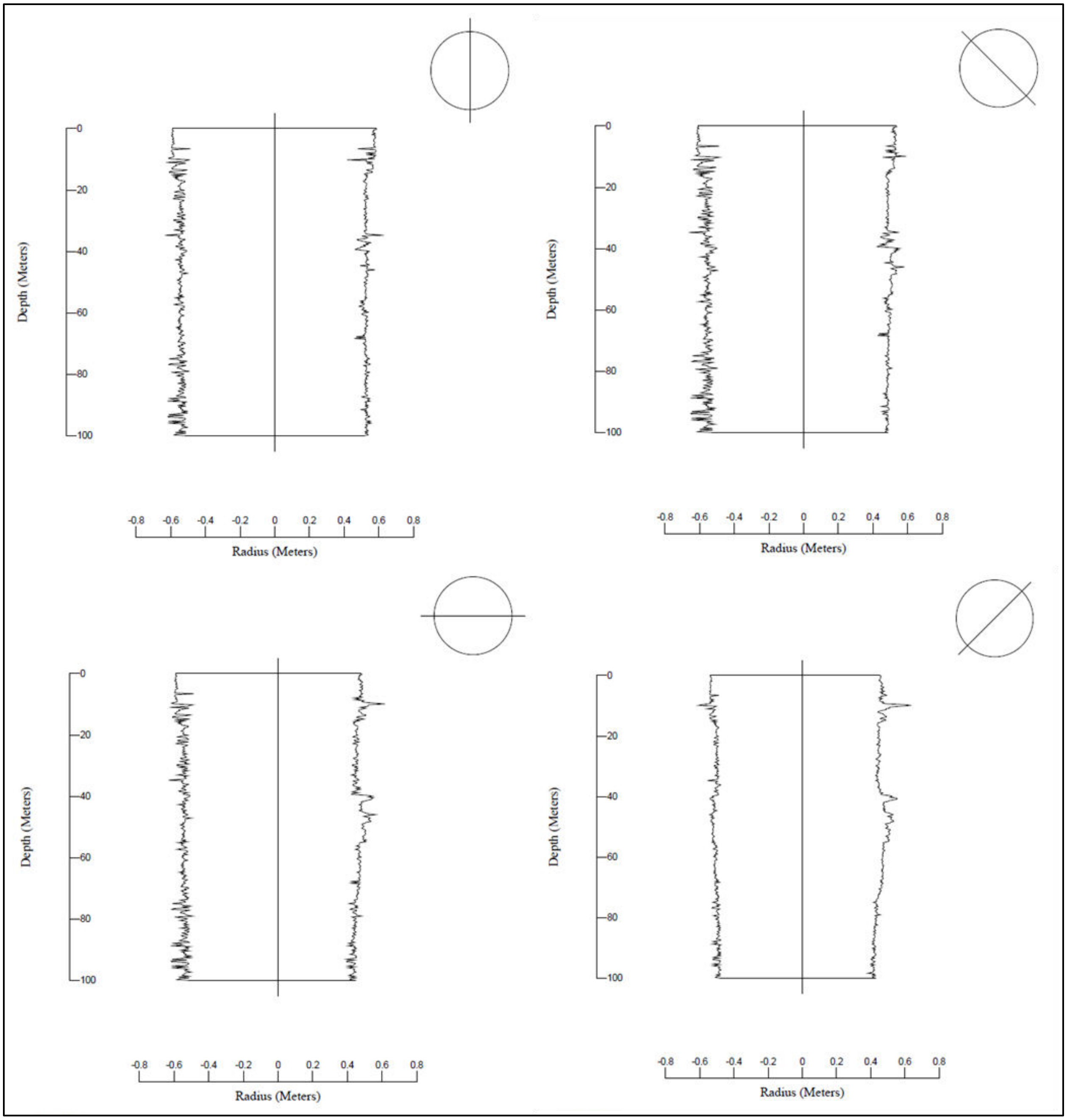

Figure 5. Ultra-sonic profiling output from SHAPE device

CONCLUSIONS

Drilled shafts are increasingly being selected for deep foundation support. To satisfy the design intent, the as-built shaft shape, shaft vertical alignment, shaft base cleanliness, cage alignment, concrete cover, and concrete integrity are all important. There are various methods available to check these design considerations. Many of these methods have inherent limitations. There are recent advances in shaft inspection tools and NDT technologies that have now overcome many of the limitations inherent in these traditional test methods, and can be deployed faster, tested sooner in the construction process, and provide additional information for the shaft shape, bottom condition, verticality and overall shaft integrity.

Drilled shafts can be quickly evaluated for excavation shape and shaft verticality with the use of the SHAPE device. This device provides the needed information with minimal time required, expediting the time to concrete the excavation. The bottom condition can be quantitatively evaluated through the use of the SQUID device. The device provides quantitative information which has never before been available to the designers. This test is typically accomplished in less time than is possible with other methods, allowing the concreting process to proceed as quickly as possible. THE thermal integrity method is the latest NDT method for drilled shafts and provides complete evaluation over the entire cross section, including the critical concrete cover region. This test is run during the concrete hydration time, which occurs soon after casting, with the typical test is completed in 12 to 48 hours after casting, allowing the overall construction process to be accelerated.

The recent advances in drilled shaft quality control methods offer owners, engineers, and contractors innovative and powerful tools for quality control and quality assurance of drilled shafts. These tests provide more complete and reliable information than what can be obtained from other traditional methods, while doing so in a greatly reduced time and thus accelerating the construction process.

REFERENCES

Piscsalko, G. and Cotton, D 2011. Non-Destructive Testing Methods for Drilled Shaft and ACIP Piles, Proceedings from Deep Foundation Institute 36th Annual Conference; pp. 525-532

Mullins, A.G., 2010. Thermal Integrity Profiling of Drilled Shafts, DFI Journal Volume 4 No.2, Hawthorne , NJ, pp. 54-64

Piscsalko, G., Cotton, D., Belardo, D., Likins, G.E., 2015. Using Thermal Integrity Profiling to Confirm the Structural Integrity of foundation applications, Proceedings of The International Foundations Congress and Equipment Expo 2015: San Antonio, TX.

Piscsalko, G., Likins, G.E., Mullins, G., 2016. Drilled Shaft Acceptance Criteria Based Upon Thermal Integrity, DFI 41st Annual Conference on Deep Foundations: New York, NY.

Brown, D. A., Turner, J.P. and Castelli R.J. (2010). Drilled Shafts: Construction Procedures and LRFD Design Methods, FHWA-NHI-10-016, Geotechnical Engineering Circular (GEC) No. 10. U.S. Dept. of Transportation, Federal Highway Administration, 970 p.