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Paper Title: Quality Control of Drilled Foundations for Base Cleanliness, Concrete Integrity, and Geometry

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ABSTRACT

One of the important factors influencing the performance of drilled foundations is the construction method and procedure. To ensure proper construction, a Quality Control process is applied during and after drilled foundations installation. Considering the construction process for each type of drilled foundation, the evaluation of the drilled hole prior to concrete or grout placing and cage lowering has to be performed using the appropriate testing method. In the case of Augered-Cast piles, the bottom of the hole cleanliness or the cross-section area evaluation are performed using different tools from those used in the case of drilled shafts.

The current state-of-practice includes several quality control inspection devices, and non-destructive test (NDT) methods to assess the quality and integrity of drilled shafts as well as augered-cast piles. Newly developed methods, can quantitatively measure the shaft base cleanliness, cross-section area, and measure elevated concrete temperatures during the hydration process of cast-in-place concrete foundations. Collectively, results from these tests and devices can be interpreted to evaluate the overall Quality Control and integrity of drilled foundations.

This paper introduces three main segments of the Quality Control of drilled foundations: (1) Base Cleanliness (2) Drilled foundation Integrity, and (3) Drilled hole Geometry. Primarily and for comparison purposes, for each one of the methods introduced in this manuscript, their equivalent or existing method used as the standard practice is presented and briefly discussed.

Keywords: Base Cleanliness, Drilled Shafts, Quality Control, Geometry, Integrity

Introduction

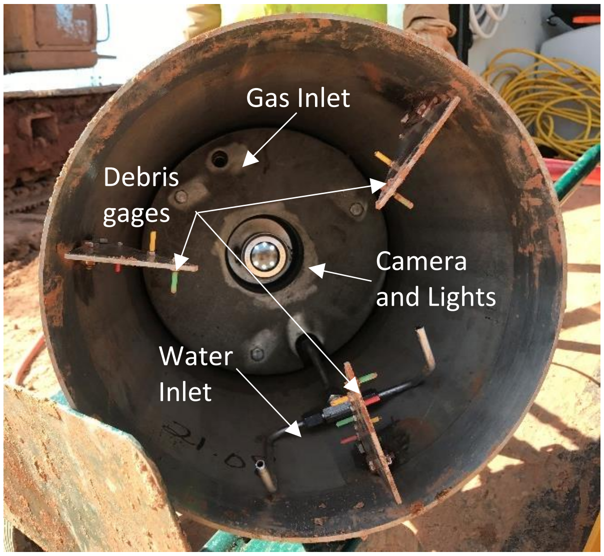
In general, every project specifications and guidelines, provide details regarding the quality control for the pertinent deep foundation system. In the particular case of drilled foundations, depending on local Department of Transportation's practice, details are provided to the interested parties regarding base cleanliness, integrity, and geometry of the drilled foundation. In some cases, all three and more testing are specified and in others selected tests are mandated. However, in either way, testing is required. For example, procedures and requirements associated with shaft base cleanliness of drilled shafts designed for federally funded projects are specified in governing guidelines such as the Federal Highway Administration (FHWA) Drilled Shaft manual [1]. In addition, each state Department of Transportation (DOT), in conjunction with the geotechnical engineer of the record, provides specifications regarding allowed debris thickness limits at the shaft base, [2]. In an effort to obtain the latest information regarding drilled foundations construction and quality control requirements, a large body of literature and governing documents published by each DOT were reviewed. This review process consisted of obtaining the latest version of the relevant document, identifying the section addressing shaft base cleanliness, geometry, and integrity. From this review it was noted that the FHWA manual presents detailed guidelines regarding the quality control and quality assurance associated with drilled foundations. Therefore, it is important to present a synthesized description of latest techniques developed for the quality control of drilled foundations.

Base Cleanliness

Several specialized inspection tools and equipment can be considered for the assessment of shaft base cleanliness as well as debris thickness determination. As a general reference, the FHWA drilled shafts manual [1] lists the tools commonly available in 2010 for quality assurance purposes including the shaft base cleanliness. The primary tool described by the FHWA is the Miniature Shaft Inspection Device (min-SID) where the shaft base cleanliness is qualitatively assessed based on photos and videos taken from the bottom of the drilled hole. Another inspection tool is the Shaft Quantitative Inspection Device (SQUID) which quantitatively evaluates the drilled shaft base cleanliness by measuring the debris thickness based on force and displacement measurements.

The mini-SID

Primarily consisting of a diving bell, the mini-SID is equipped with a high definition camera, a light source, inlets for compressed gas and water, and three debris thickness gages located within the camera range. The test consists of locating the mini-SID on top of the drilled hole and lowering it into the hole by using a winch, Figure 1. After reaching the bottom of the drilled hole, the compressed gas will displace the fluid out of the diving bell creating a slurry free zone, and a photograph of the base conditions is taken, Figure 2. The debris gages will indicate the approximate debris thickness. It is important to note that the outcome of this test is not a quantitative evaluation and the debris thickness is marked as: "< 0.5inches" or "> 0.5inches" etc.



(a)

(b)

Figure 1. Miniature Shaft Inspection Device, Ref [4] (a) Diving Bell, and (b) Preparing for testing

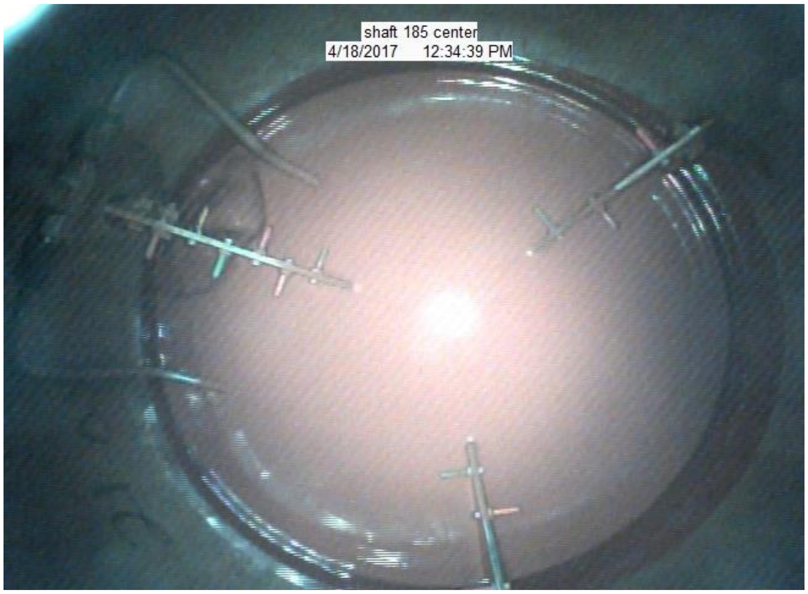


Figure 2. min-SID picture taken at the bottom of a drilled shaft, Ref. [4]

The SQUID

The SQUID device has an octagonal shape with a maximum diagonal length of 25.5-inches (647-mm) and height of 25.0-inches (635-mm). Three penetrometers and three retractable displacement plates are part of the device which are used to record force and displacements simultaneously. The penetrometers are designed to have conical or flat tips with an average cross-sectional area of 1.55-in^2 (10-cm^2), Figure 3. The resistance to penetration is measured by strain gages, with the capability of recording up to 14-ksi (100-MPa) of stress. The test procedure consists of mounting the device on the Kelly-Bar and lowering it into the drilled hole. Once the device is located at the bottom of the hole, the buoyant weight of the Kelly-Bar will transfer sufficient force for the probes to measure the force needed to penetrate into the debris and bearing layers and for the displacement plates to retract measuring the corresponding displacements. The corresponding forces and displacements are recorded. Real-time force versus displacement plots are generated and displayed in the SQUID Tablet, Figure 4.

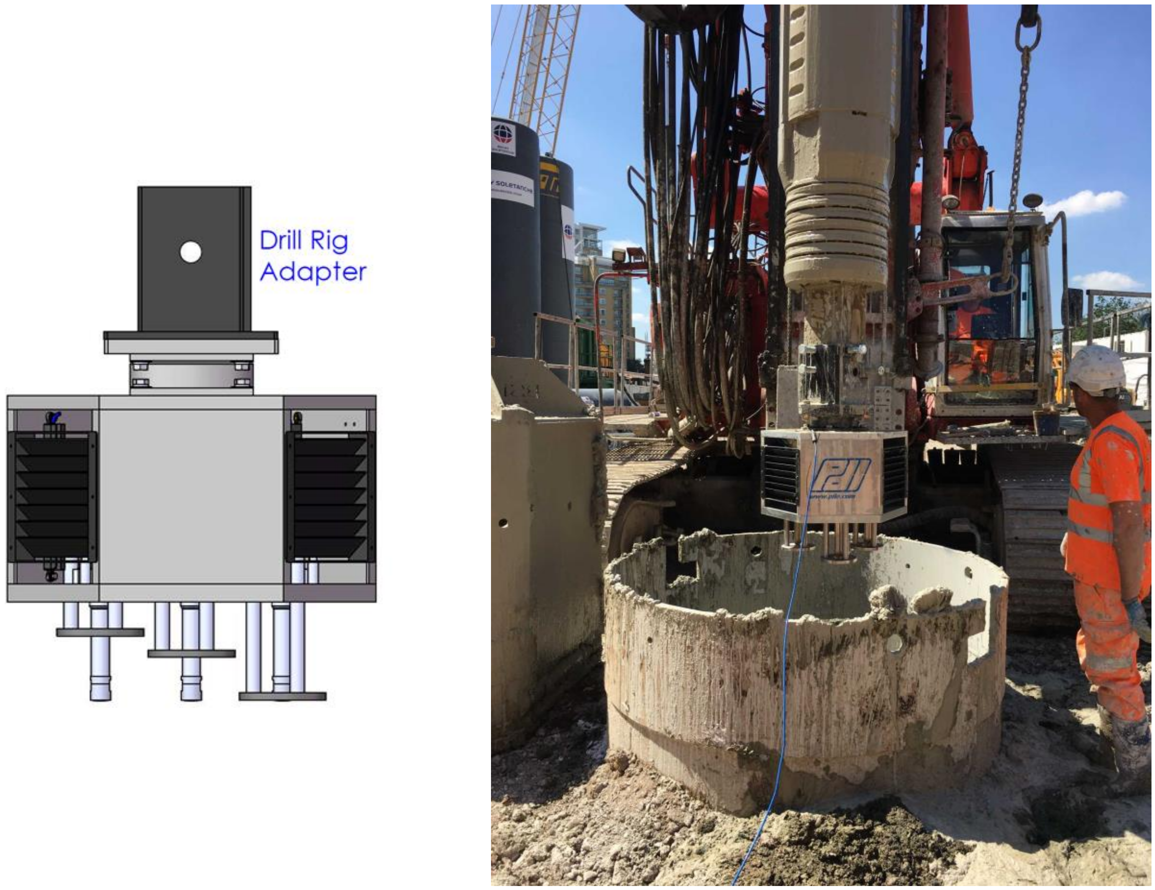


Figure 3. Shaft Quantitative Inspection Devices (SQUID), Ref. [4]

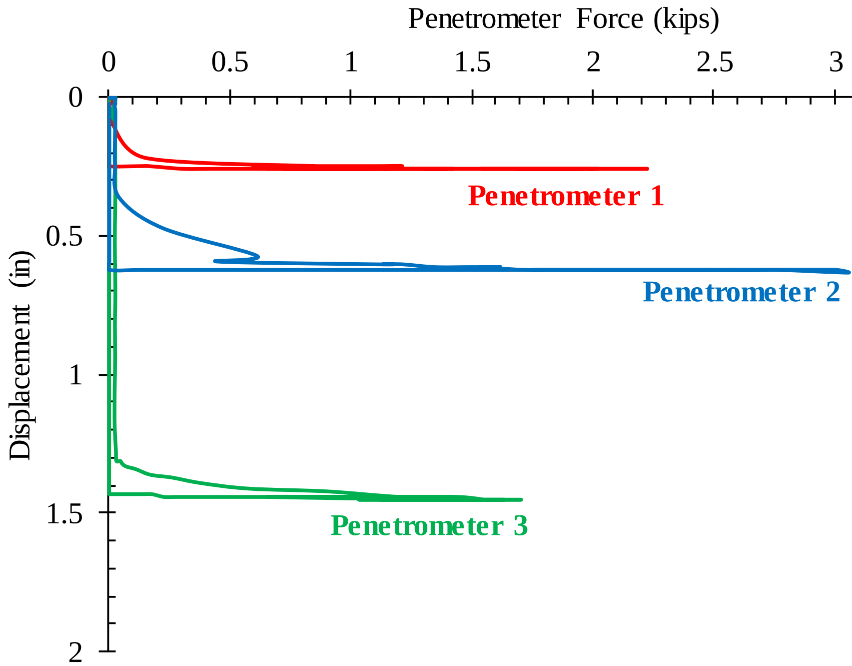


Figure 4. Force and Displacement plot from a SQUID Testing, Ref. [4]

Debris Thickness

Based on the consistency of a debris material, it is reasonably assumed that a material categorized as debris will have strength properties similar to a soft to medium clay with an unconfined compressive strength ranging between 0.25-ksf (12-kPa) and 2-ksf (95-kPa), and a unit weight ranging between 100-pcf (16-kN/m^3) and 120-pcf (19-kN/m^3). With these strength parameters and applying the general bearing capacity theory proposed by [9] for circular foundations, equation (1), the resistance to penetration of a flat tip with a cross section area of 1.55-in^2 (10-cm^2) was determined to be between 0.020-kips (0.089-kN) and 0.160-kips (0.712-kN).

$$q_{ult} = 1.3 s_u N_c \tag{1}$$

Where q_{ult} is the ultimate bearing capacity of a circular base, s_u is the undrained shear strength of the material, and N_c is the bearing capacity factor.

According to the results obtained from equation (1), a debris layer is defined as a material that has a minimum and maximum resistance to penetrometer force of 0.020-kips (0.089-kN) and 0.160-kips (0.712-kN), respectively.

Debris thickness thresholds can be plotted on the force-displacement curves to determine the debris thickness following the above described characteristics, as in Figure 5a and 5b. Figure 5a illustrates the results of a SQUID test presented as a force-displacement plot including debris thickness thresholds. This plot includes the test's loading and unloading stage where the force and displacement gradually increases to a maximum and returns to zero values as the device is unloaded. For illustration purposes, Figure 5b is an enhancement (i.e. zoom-in capture) of the threshold lines, and the debris thickness is calculated by subtracting the displacement corresponding to the soil/rock-threshold (0.160-kips) from the debris-threshold (0.020-kips).

For a project located in Oklahoma, the debris thickness obtained using the SQUID has been correlated to the results obtained by using the mini-SID. According to [4], for seven drilled shafts a side-by-side base cleanliness test was performed and the results suggest that with an R^2 value of 57% there might be a statistical correlation between debris thicknesses obtained using the mini-SID and SQUID.

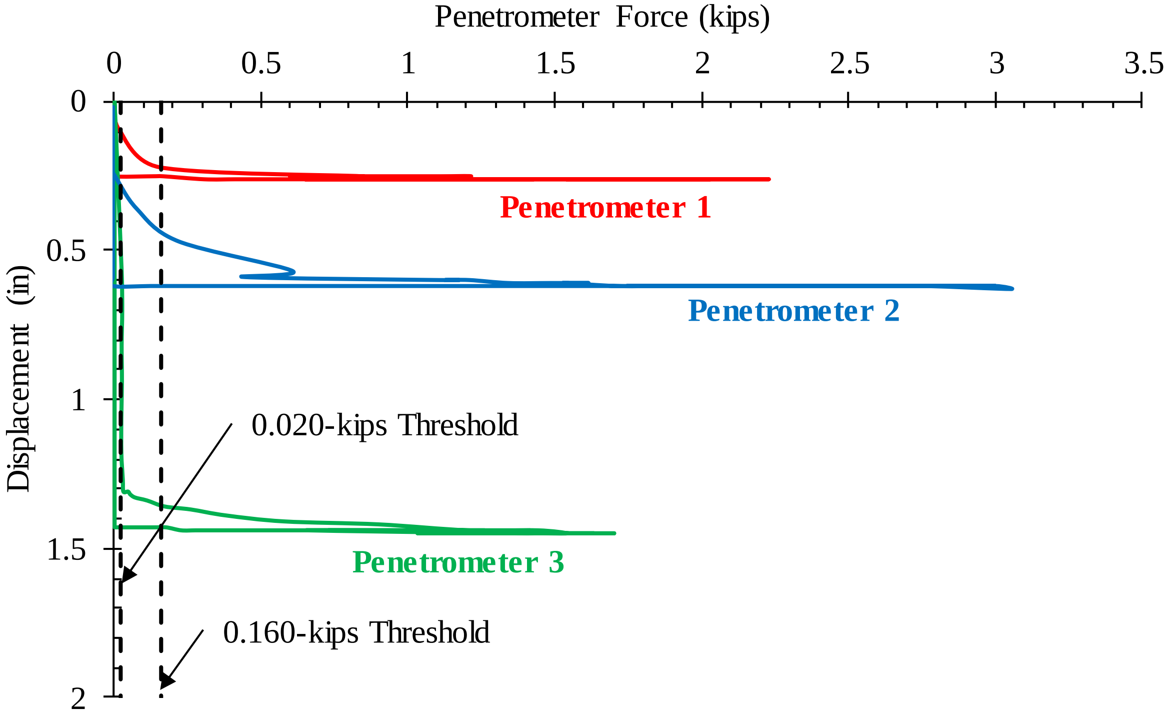


Figure 5a. Debris Thickness from SQUID testing, Ref. [4], Overall Thresholds

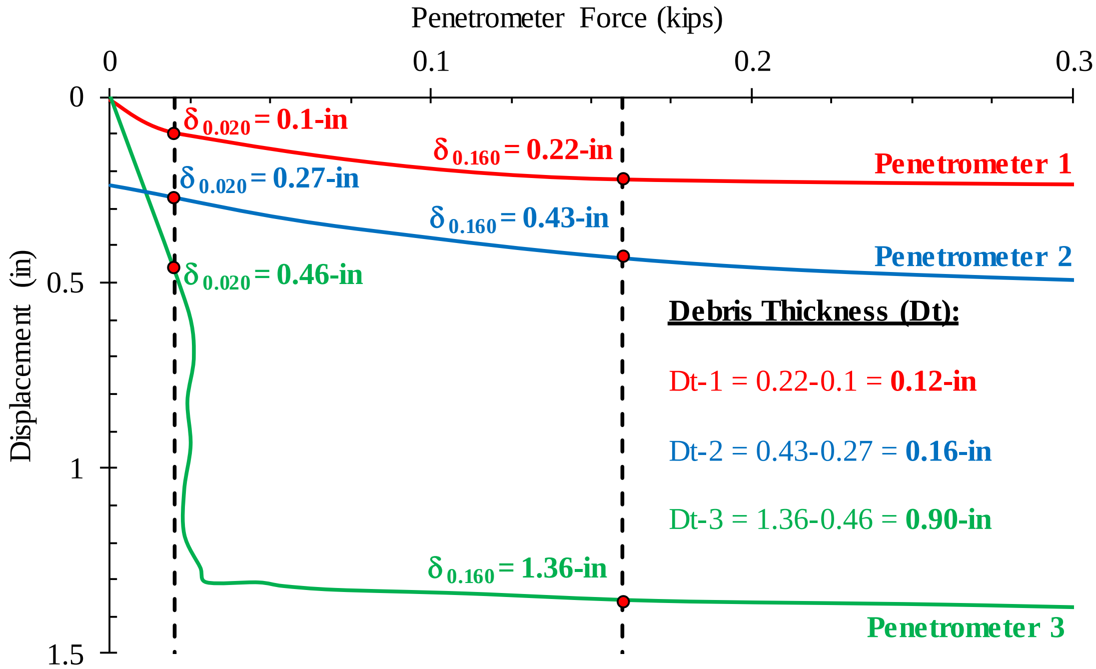


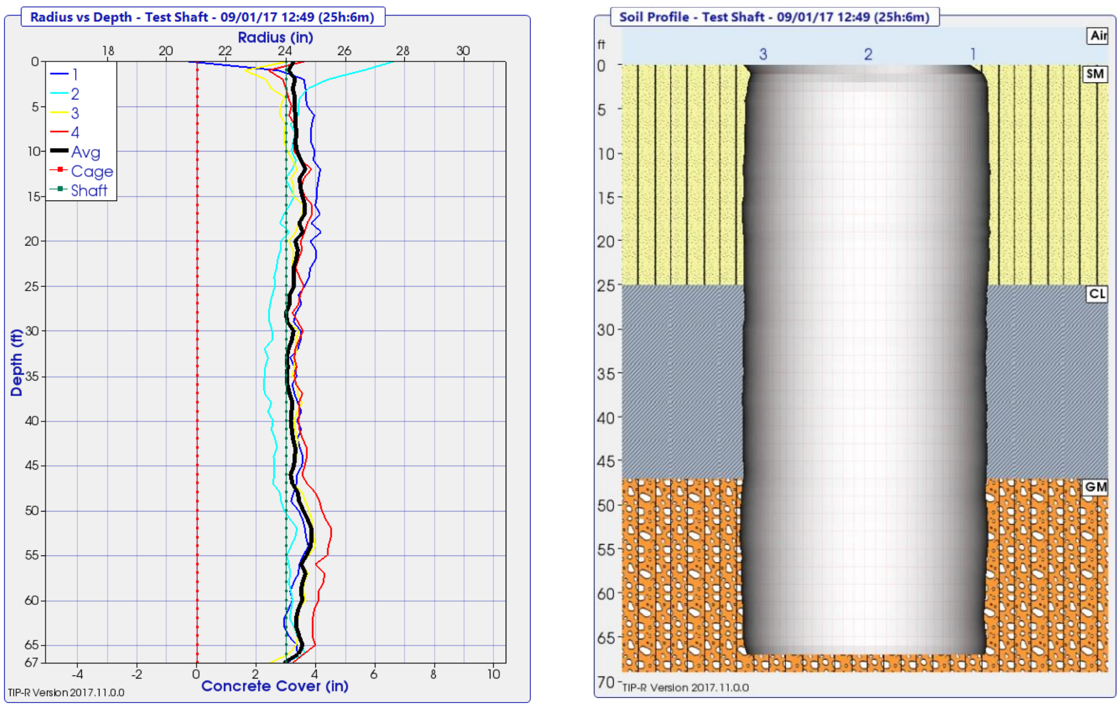
Figure 5b. Debris Thickness from SQUID testing, Ref. [4], Debris Thickness Calculation

DRILLED FOUNDATION INTEGRITY

Due to the large axial and lateral capacities drilled shaft foundations have become very popular and vastly used for federal and private projects. As previously mentioned, due to construction process associated with drilled foundations, certain quality control process become very difficult to complete. During the drilling process and concrete placing, some factors such as drilling cuttings, underground water flow, unproperly placed concrete, etc. could significantly impact the foundations quality. Several NDT methods are available to evaluate the integrity of completed shafts.

Thermal Integrity Profiler

The Thermal Integrity Profiling is an NDT method which uses the heat generated by hydrating concrete to determine the integrity of the drilled shaft. These temperature measurements are obtained throughout the shaft length using thermal sensors [5], [6], [7]. Additional information such as reinforcing cage eccentricities and concrete cover can be obtained from the TIP analysis. Furthermore, this method allows for detection of defects within the rebar cage as well as in the cover area. For example, if a series of drilled shafts are used for a retaining wall project (i.e., secant or tangent walls), the cover and the verification of concrete flowing around and through the cage to provide pertinent cover becomes important. Local temperatures are converted to local radii based on temperature measurements at various locations along the drilled shaft or augered-cast pile as well as the total concrete volume, Figure 6.



(a) **(b)**

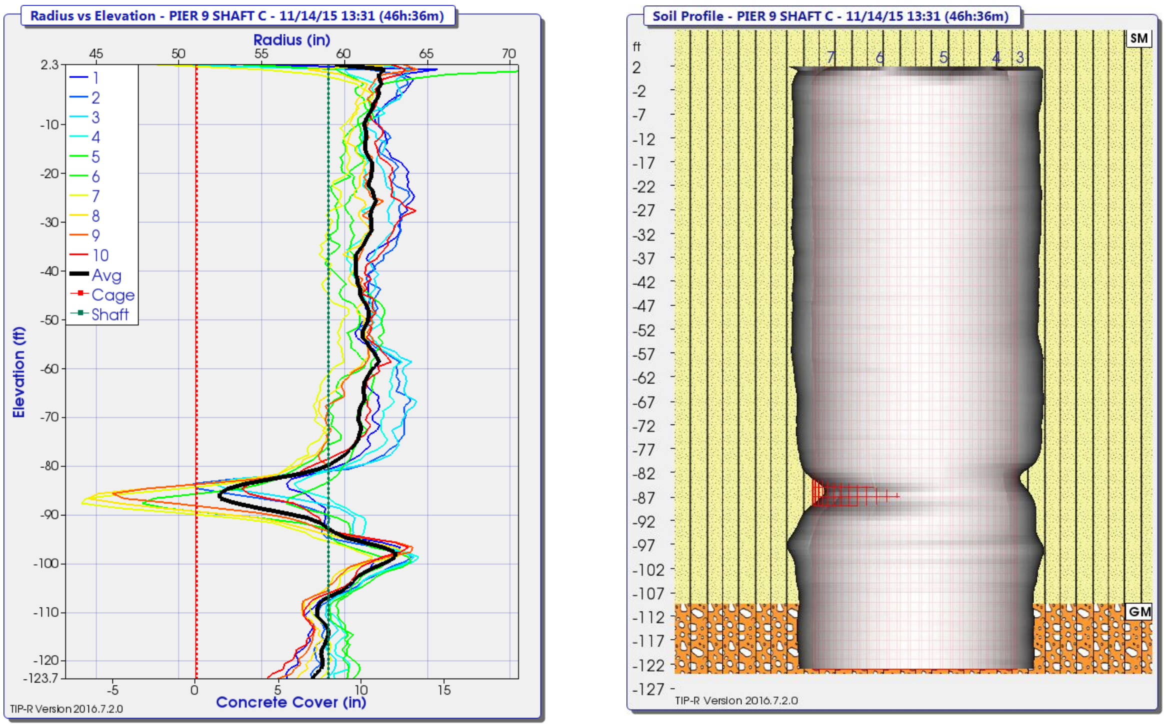
Figure 6. TIP results for a satisfactory drilled shaft **(a)** Effective Radius Vs. Depth and **(b)** 3D Model overlaying the Soil Profile

Curing concrete will exhibit a normal heat signature which is dependent upon the shaft diameter, concrete mix design, concrete quality, and soil conditions. A local reduction in cement content within the concrete will interrupt the normal temperature signature and will be measured by the TIP as a locally reduced temperature in the area of the defect when compared to the overall average temperature. This defect will also be seen in adjacent measurement locations, with a diminished effect at more distant measurement locations. Any temperature measurements which are cooler than the average temperature are areas of reduced cement content which can be a reduction in concrete volume (i.e., defect) or poor concrete quality. Temperature measurements with a higher local temperature than the average temperature are areas of increased concrete volume (i.e., bulge).

The TIP test can also evaluate the reinforcing cage alignment by comparing temperature measurements from diametrically opposite locations versus the overall average temperature at the same elevation. If one temperature measurement location is cooler than the average temperature, and the diametrically opposite temperature measurement location is warmer than average temperature, this indicates that the cage is not centered. The cooler measurements indicate this area of the reinforcing cage is shifted towards the soil interface while the warmer measurements indicate this area of the reinforcing cage is shifted towards the shaft center. This cage alignment analysis provides additional information on concrete cover, as a reinforcing cage that is shifted to the excavation sidewall can result in little or no concrete cover in this region even without having a defect present. These effects and analyses are further explained by the following example.

Considering Figure 7, the Effective Average Radius (inches) vs. Elevation (feet), Figure 7a, and the 3D image of the drilled shaft, Figure 7b, are created based on the reported concrete volume and reported cage radius. The Effective Average Radius is the computed average radius at a given depth based on the average of all recorded local temperatures. The vertical dashed green line represents the design or intended shaft diameter, the vertical dashed red line represents the edge of the reinforcing cage, and the estimated cover beyond the reinforcing cage is shown on the bottom x-axis. Note that from the top of shaft to Elevation (EL) -78.00 the Effective Average Radius is slightly greater than the design shaft radius of 59 inches. This slightly oversized region is consistent with the reported concrete over pour. Beginning at EL-78 the Effective Average Radius reduces down to 52 inches near EL -85.70. The Effective Local Radii reduce to approximately 44 to 45 inches near Wires 7 and 8. An increase in cover or excess concrete is evidenced by higher recorded temperatures near EL -98. The Effective Average Radius is relatively consistent with the design radius from EL -106 to the base of the shaft.

Due to the estimated reduction in radius to inside the reinforcing cage shown in Figure 7, the drilled shaft was cored to try to locate the extent of the anomaly, Figure 8. Since coring outside the cage is in most cases not feasible, the first core was reportedly drilled 18-inches inside the reinforcing cage between Wires 7 and 8. This location was selected due to Wires 7 and 8 showing the maximum reduction in radius. The core was angled slightly so that near EL -87 the core would be in close proximity to the cage. As shown in Figure 8, the results of coring showed the poor quality of concrete which could have been missed if the coring would have been done through the center.



(a) **(b)**

Figure 7. TIP Wire results for a defective drilled shaft **(a)** Effective Radius Vs. Elevation and **(b)** 3D Model overlaying the soil profile

Figure 8. Coring results in a defective drilled shaft

DRILLED FOUNDATION GEOMETRY

Drilled shafts are being increasingly used as a deep foundation element due to their ability to carry large loads. These shafts are difficult to inspect prior to the concrete casting process, particularly when there are drilled under wet conditions. The excavation shape, cross-sectional area, and verticality are being inspected using various techniques to verify design compliance. Depending on the foundation diameter, the verticality plays an important role during load transfer process and in cases where the foundation is rock socketed, the verticality could significantly impact the foundation performance under eccentric loads at the transition zone between soil and rock.

The various inspection techniques used include concrete volume plots determined using a weighted tape, mechanical calipers using spring loaded arms and electronic calipers using ultra-sonic signals. The advantages and limitations of each of these methods, along with a new inspection device are presented below.

Concrete Volume Plots

The most basic method for determining the excavation shape is the use of manually created concrete plots, Figure 9. This method determines the shape of the excavation by using a weighted tape to measure the top of concrete elevation relative to the placed concrete volume. This test method provides a crude estimation of the excavation shape as it relies completely on the skill level of the individual taking measurements with the weighted tape and further relies on the reported truck volumes from the ready-mix plant, making the method subjective with no quantitative measurements.

The Mechanical Caliper

The drilled hole shape could also be assessed using a mechanical caliper which relies upon a device consisting of two or four spring loaded arms that contact the excavation sidewalls as the device is lowered and/or raised through the excavation, Figure 10. The arm movement is measured electronically to determine the distance from the center to the sidewall at the various measurement points. The mechanical devices must be advanced slowly to insure the arms remain in contact with the sidewall and do not slip during advancement. The mechanical caliper provides a minimal amount of quantitative data (geometry determined from data taken on either 90°or 180° axis) depending upon the number of spring loaded arms and relies upon these arms staying in contact with the sidewalls during the entire lowering/raising process.

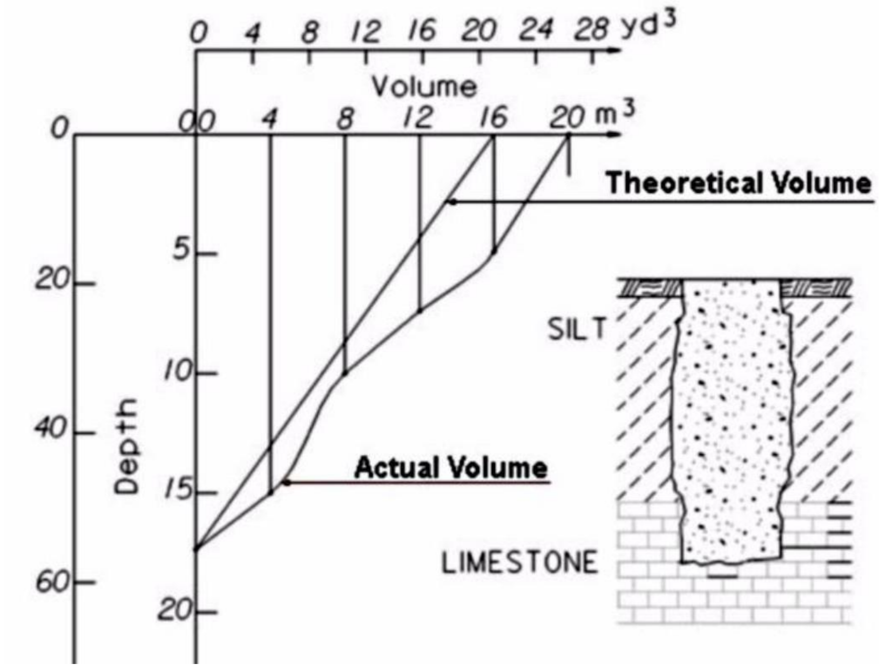
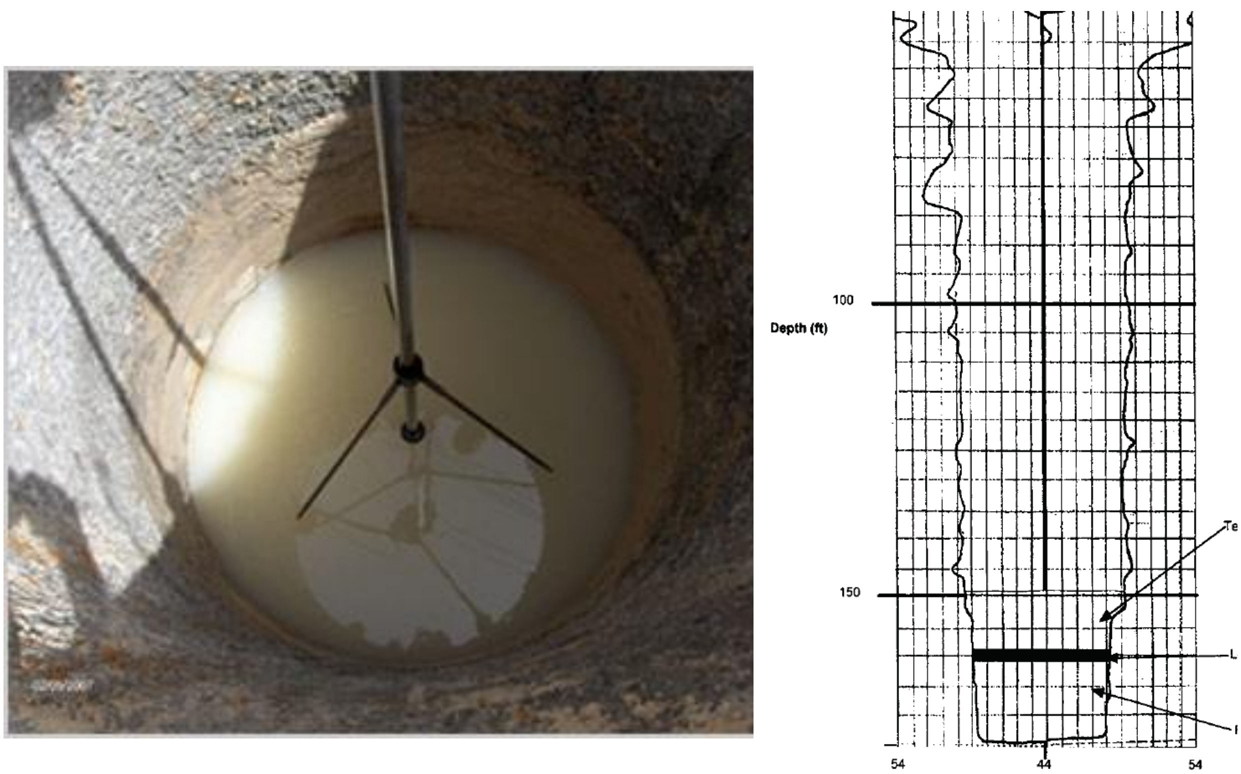


Figure 9. Concrete Volume-Depth Plot to assess drilled hole shape, Ref. [2]

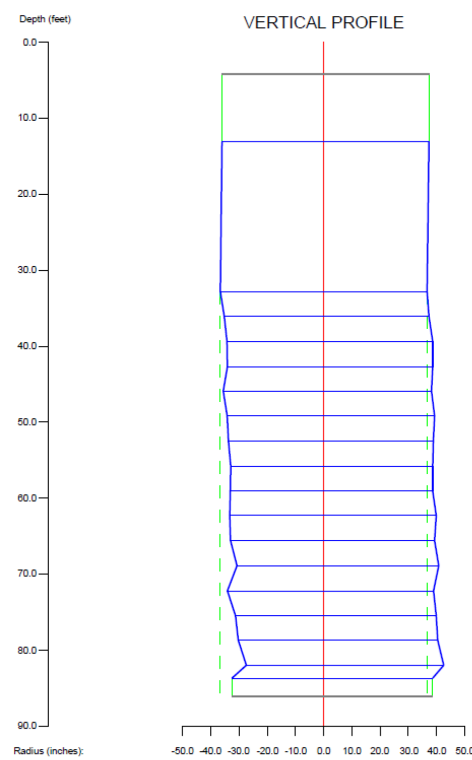


(a) **(b)**

Figure 10. Mechanical Caliper **(a)** During testing, Ref [X], and **(b)** Results, Ref [1]

Sonar Caliper

The electronic caliper method involves transmitting an ultra-sonic pulse through a wet cast excavation and receiving the pulse which has reflected off the excavation sidewall. The distance to the sidewall is calculated from one half the measured transmit/receive pulse time multiplied by the wave speed of the slurry material, Figure 11. Some electronic calipers have two or four ultra-sonic sensors mounted in fixed positions and thus providing a minimal amount of quantitative data (geometry determined from data taken on either 90°or 180° axis). Other electronic calipers are rotated 360° at discrete elevations to obtain these transmission times, providing a greatly increased number of data measurements at each measurement elevation. The caliper depth within the slurry is measured via a depth encoder located at the surface, tracking a cable connected to the electronic caliper. The distance to each sidewall is calculated using an assumed wave speed or a wave speed that is measured only near the surface. As soil particles segregate within the slurry, these particles naturally sink to the bottom of the excavation, increasing the slurry density and changing the wave speed with depth. This changing slurry properties as a function of depth, and thus a changing wave speed as a function of depth, can cause significant errors in the shape or cross-section calculation.



(a) **(b)**

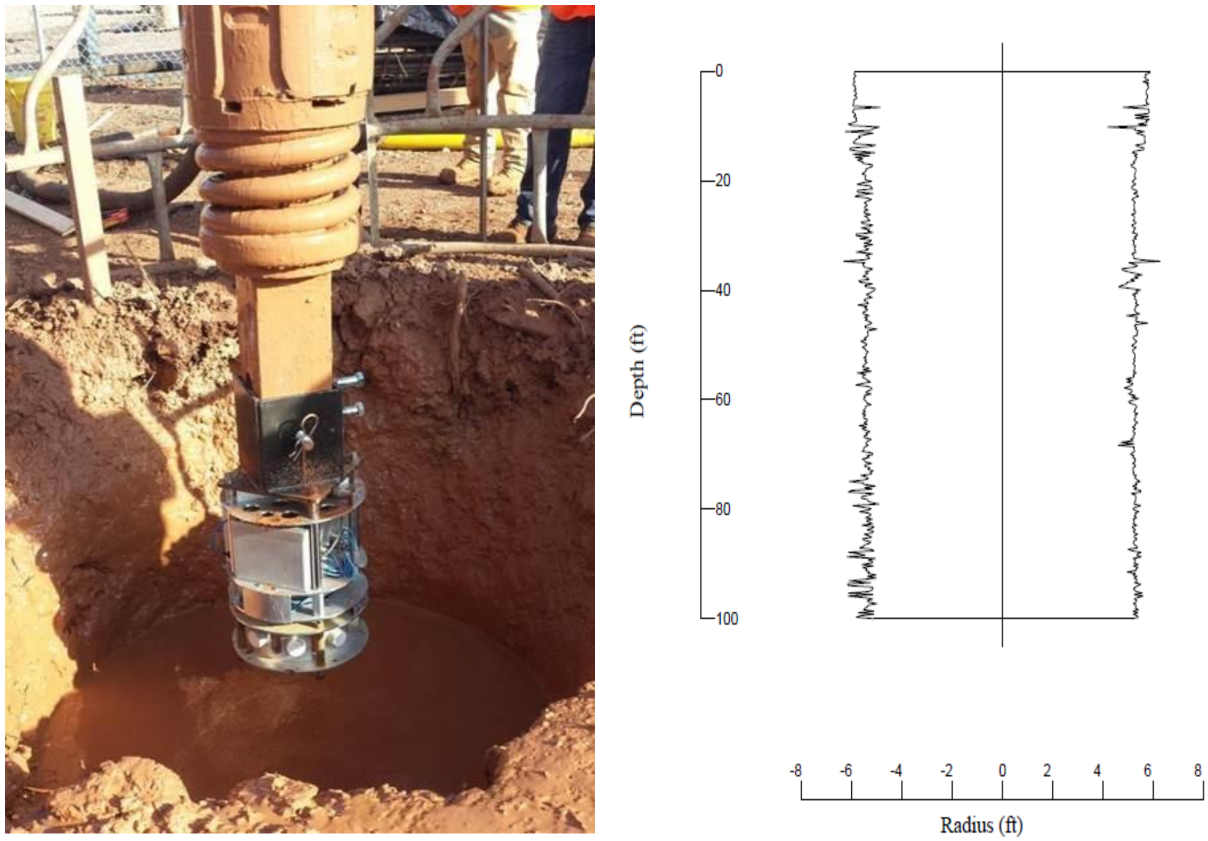
Figure 11. Sonar Caliper **(a)** prior testing, Ref. [3] and **(b)** results after testing, Ref [8]

Shaft Area Profile Evaluator (SHAPE)

The SHAPE device attaches to the Kelly-bar stub and collects data while advancing down the excavation at comparatively high rates of speed (approximately 305mm/second (1 foot/second) advancement rate). This advancement rate greatly reduces the time required to profile the shaft sidewalls. The device simultaneously transmits and receives ultra-sonic signals from eight individual sensors mounted 45 degrees apart, providing the needed resolution to more accurately determine the excavation geometry, Figure 12. If additional resolution is required, the device can complete the downward scan, then the Kelly-bar can be rotated the appropriate degree with additional data taken at each depth location while the device is raised to the surface.

To overcome the variability in slurry wave speed, the SHAPE has an integrated self-calibrating feature which measures the transmission time through the slurry at each depth measurement location utilizing a transmitter and receiver pair that are mounted a known distance apart. Each radii calculation is performed using the actual measured wave speed at its respective depth, thus improving the accuracy of the computed radii and overall verticality of the excavation. The device operates with no electronic cables needed for data transmission from the device to the surface, thereby keeping personnel away from the open excavation during the test. When the device is raised to the surface, the measured data is transmitted to a tablet computer located a safe distance from the excavation, to further evaluate.

The eight sensors and frequency of the transmitted and received signals allow the device to acquire a highly quantitative excavation shape while allowing the device to be lowered at a high and constant rate on the drilling stem with no stopping required at each measurement location as other devices require.



(a) **(b)**

Figure 12. SHAPE device **(a)** before testing, and **(b)** Testing Results

Summary and Conclusions

Considering the primary objective of testing drilled foundations combined with the impact of time effectiveness on construction project schedules, the new implemented methods for testing the base cleanliness, integrity, and geometry of drilled foundations could benefit the construction quality and schedule by providing reliable and efficient results. The ability of quantitatively assessing the quality of the drilled foundations provides a more basis for the overall evaluation of deep foundations. It is important to reiterate that a properly documented construction process including quality control of materials, quality control of the drilling process, and the inspection of the drilled hole prior to placing concrete lead to a high-quality foundation construction. Therefore, equipment and methods that help to achieve this objective are always benefiting the industry only if the process is completed safely, validly, and efficiently, strictly in that order.

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