Quantitatively assessing the geometry and base conditions of drilled shaft excavations

Benjamin A. White, P. E.[i], C. Michael Morgano, P. E.[ii], Brandon Phetteplace, P.E.[iii]

i) Senior Engineer, GRL Engineers, Inc., 30725 Aurora Road, Solon, Ohio 44139, USA

ii) Vice President, GRL Engineers, Inc., 30725 Aurora Road, Solon, Ohio 44139, USA

iii) Vice President, GRL Engineers, Inc., 1420A Stonehollow Dr., Kingwood, Texas 77339, USA

ABSTRACT

Drilled shafts are common foundation elements used for structural support all around the world. The quality of construction of a drilled shaft is critical due the large structural loads and often limited redundancy of many drilled shaft foundations.

Many design codes allow for consideration of end bearing in the design, and assume certain conditions at the bottom of the foundation. For shafts designed to resist loads using end bearing, the shaft bottom condition is of particular interest. Some current methods to evaluate the shaft bottom condition are to send an inspector to the bottom of a dry excavation or to retrieve video of the shaft bottom using specialized equipment. Clearly, sending a person to the bottom of an excavation is not desirable from a safety standpoint. A video of the bottom of the shaft may provide a visual interpretation of the condition of the soil/rock at the base of the shaft, but provides no clear debris/sediment thickness or quantitative measurements of material strength.

Recently, test equipment and evaluation methods have been developed to safely collect measurements at the bottom of a drilled shaft and evaluate debris thickness and competency of the bearing material. The Shaft Quantitative Inspection Device (SQUID) is a downhole device that collects force and displacement measurements as load is applied and the shaft bottom material is penetrated. Three individual measurements of force and displacement are collected simultaneously, and viewed in real time during testing. The resultant force-displacement curves are evaluated for debris/sediment thickness as well as soil/rock strength.

Foundation excavation geometry and verticality are of interest to be sure the structure load is transmitted axially down the foundation element and no unexpected moments are introduced into the foundation. In addition, if unexpected drilling or ground conditions are encountered, measurement of the geometry of the excavation can identify areas of concern and lead to proper corrective procedures. Current industry methods for measuring shaft verticality include physical measurement or sonic measurements at chosen intervals. Often these methods require mobilization of additional equipment to complete the measurement and can be time consuming.

The SHaft Area Profile Evaluator (SHAPE) is a downhole device that collects sonic measurements of the shaft geometry every 1 second in 8 directions simultaneously. The results are downloaded shortly after data collection and automatically processed to provide a near immediate rendering of the shaft geometry and verticality. The SHAPE can be deployed using the drill rig or a winch system and data is typically collected at a rate of 1 linear foot per second. SHAPE systems are available for measurements in any type of drilling fluid or in dry conditions.

The SQUID and SHAPE have been used on many projects over the last several years for evaluation of shaft quality of construction. This paper will present general test results as well as cases where interesting data were observed. In addition, suggestions for best practice when testing and proper implementation of specifying the SQUID and SHAPE equipment and test methods will be provided.

Keywords: drilled shaft, caisson, geometry, verticality, cleanliness, base condition, testing

1 INTRODUCTION

Drilled shafts are increasingly being selected as a deep foundation element due to the large axial and lateral capacities that can be attained. Because of these larger capacities, the number of foundation units required to support a structure can typically be reduced, especially for larger structures. This reduced foundation redundancy has made it even more important to verify that the drilled shafts are both structurally sound and are able to support their required loads.

For typical drilled shaft projects, the project specifications provide details regarding the quality control procedures to be used during the construction of the shafts. These specifications generally address items such as shaft geometry, verticality, base cleanliness, concrete quality/shaft integrity, and reinforcement cage alignment. Load testing to verify geotechnical design parameters is also sometimes addressed.

Many of the quality control test methods currently used are time consuming, do not provide quantitative information, do not address all design considerations, or cannot be performed until the shaft has cured for several days. Several recent advances in drilled shaft quality control testing techniques address these issues.

2 CURRENT PRACTICE

2.1 Shaft Excavation Geometry

To evaluate drilled shaft shape, plots of concrete volume placed versus elevation have historically been used to identify enlarged areas where concrete may be filling voids as well as areas where the concrete volume placed is less than anticipated. Additionally, shaft sidewalls have been profiled using either mechanical calipers or ultrasonic profiling devices to determine the excavation geometry and verticality.

The use of these procedures and equipment tends to be relatively time consuming and poses safety concerns since personnel must work near an open excavation to take measurements and setup equipment. Also, depending on the profiling device, there may not be sufficient resolution to adequately define the excavation geometry.

2.2 Shaft Excavation Base Cleanliness

The performance of the drilled shaft could be affected by an excessive accumulation of unsuitable loose material at its base. The cleanliness of the shaft bottom has traditionally been evaluated by bouncing a weighted tape off the bottom of the shaft excavation and qualitatively assessing the base cleanliness. In some instances, inspectors have been lowered to the bottom of a dry excavation to evaluate the bottom cleanliness or a video camera has been used to view the bottom of an excavation. Obviously, sending a person to the bottom of an excavation is an undesirable option from a safety standpoint. A video of the bottom of the shaft can give a visual interpretation of the condition of the soil/rock at the base of the shaft, but provides no quantitative measurements of material strength.

For a visual assessment and documentation of base conditions, equipment such as a Miniature Shaft Inspection Device (Mini-SID) has been used. This device consists of a diving bell equipped with a high-definition camera, inlets for compressed gas and water, a light source, and three debris thickness gages located within the view of the camera (Moghaddam et al. 2018). After cleaning out the excavation, the device is lowered into the hole using a hoisting system and several shaft base images are obtained by the camera and are qualitatively analyzed to assess the conditions at the shaft base.

The use of the weighted tape is a highly subjective evaluation of base cleanliness and is dependent on the judgement of the user. While the Mini-SID provides a better estimate of sediment thickness, based on visual scaling, it may not provide a quantitative value of base debris thickness or measurements of material strength.

3 RECENT ADVANCES

3.1 General

Some recently developed drilled shaft quality control testing equipment and techniques address many of the limitations of the traditional testing procedures discussed above. These developments offer owners, engineers, and contractors alternative tools for quality control and quality assurance of drilled shafts. They provide quantitative results and can lead to accelerated construction schedules and cost savings.

3.2 Shaft Excavation Geometry – SHAPE

The most recent advance in drilled shaft geometry and verticality evaluation is the Shaft Area Profile Evaluator (SHAPE) device. This device can be used in either wet or dry cast installations. The SHAPE quickly attaches to the drill Kelly bar, a crane or hoist line, or is lowered using a winch system, and can collect data while travelling down and back up an excavation at comparatively high rates of speed (0.305 m/sec). This greatly reduces the time required to profile the shaft sidewalls and allows the concreting to begin in a much shorter time than previously possible. Figure 1 shows the device being deployed into a wet excavation by the drill rig Kelly bar.

Fig 1. Shaft Area Profile Evaluator being lowered into a drilled shaft excavation.

The major components of the device when testing in the wet are eight ultrasonic transmitters, eight ultrasonic receivers, a calibration sensor, two pressure transducers, a gyroscope, and a hard drive for data storage. The calibration sensor determines the wave speed at each test depth by measuring the travel time across the known calibration distance. The travel time to the excavation sidewall and back is then measured by the ultrasonic transmitters and receivers. This time, along with the associated wave speed, is used to calculate the distance to the sidewall. The gyroscope finds magnetic north and tracks the orientation of the SHAPE unit, which is corrected for any rotation by the SHAPE software. The corresponding test depth is determined from two pressure sensors, one above and one below the sensor array (Hannigan et al. 2021). When testing in a dry excavation, the SHAPE uses LiDAR camera technology to measure the distance to the side wall and a laser distance finder to measure the distance from the shaft bottom.

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. The device also requires no cables for data transmission thereby keeping personnel away from the open excavation during testing.

A screen display of the ultrasonic signals from a SHAPE test is presented in Figure 2. Each row displays the signal from each ultrasonic receiver with the corresponding sensor identification number (beginning with sensor 1 at the top). The bottom row displays the calibration pulse at the test depth. From the displayed calibration signal for this test, the wave speed of 1,540 m/sec was determined for the support fluid. Sensors 2, 3, and 4 have the longest arrival times indicating that the distances from the center of the device to those excavation sidewalls are the furthest. Conversely, sensors 6 and 7 have the fastest arrival time indicating that the distances from the center of the device to those excavation sidewalls are the shortest. Figure 3 presents an X-Y plot of the excavation radius from the SHAPE device's starting centroid. The data indicate that the centroid of the excavation at this depth is west and slightly south from its starting coordinates.

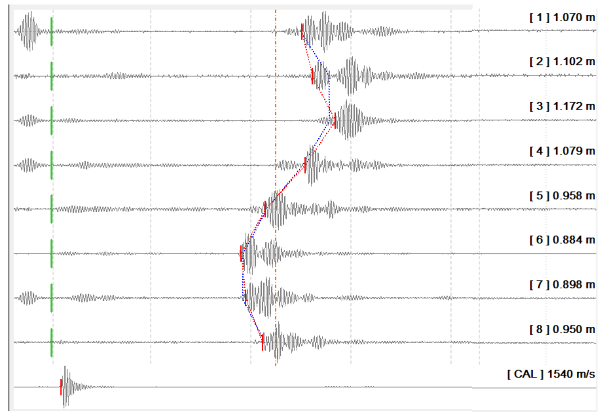

Fig 2. Ultrasonic signals at one test depth.

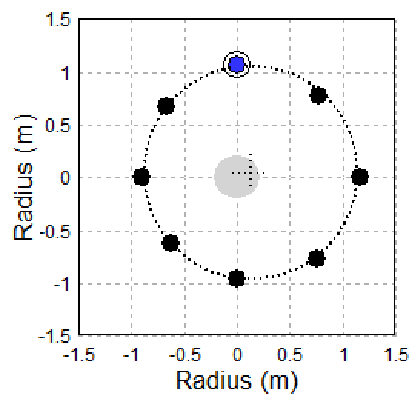

Fig 3. X-Y plot of excavation at the selected depth in relation to the top of shaft centroid

Figure 4 presents profiles of sensors 5-1, 6-2, 7-3, and 8-4, top left to bottom right. Note that sensor 1 and sensor 5 are oriented to the north and south in this case, respectively.

In this example, the centroid of the base of the excavation is clearly southwest of the centroid of the top of the excavation. The calculated eccentricity in Profiles 5-1, 7-3, and 8-4 ranged from 0.01 m to 0.12 m. Figure 5 presents the maximum calculated eccentricity in the excavation and the resulting verticality of 0.93%.

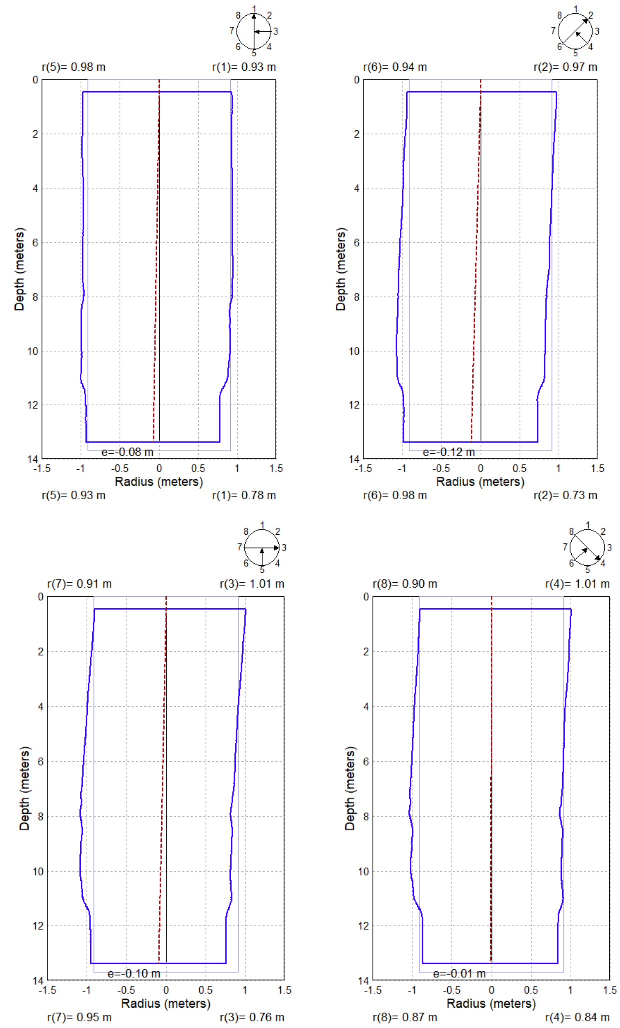

Fig 4. N-S (5-1), NE-SW (6-2), E-W (7-3), and SE-NW (8-4) profiles of radius vs depth through excavation.

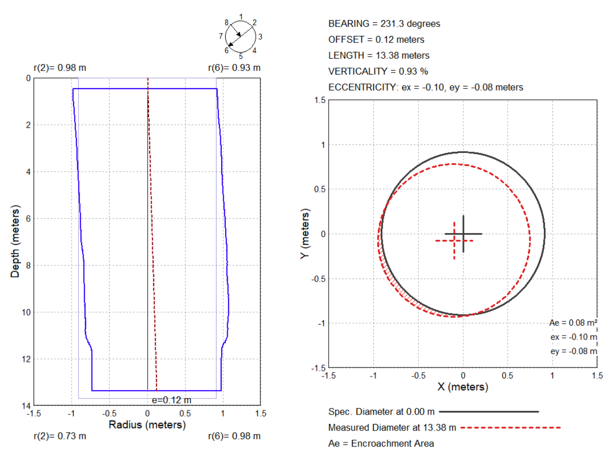

Fig 5. Maximum calculated eccentricity and resulting excavation verticality.

The next example, on an infrastructure project, the drilling contractor spent several days attempting to clean the bottom of a drilled shaft that included a casing extended to the assumed top of bedrock. Finally, a decision was made to perform a SHAPE test to evaluate the excavation. The results of the test are presented in Figure 6. A clear increase in shaft diameter is indicated just below the bottom of the casing. Based on the SHAPE testing results, the conclusion was made that the casing had not been advanced to the top of bedrock and soil was caving in. This soil caused the problems cleaning the shaft bottom. The casing was advanced additional depth, the shaft bottom was cleaned, and shaft construction continued as expected.

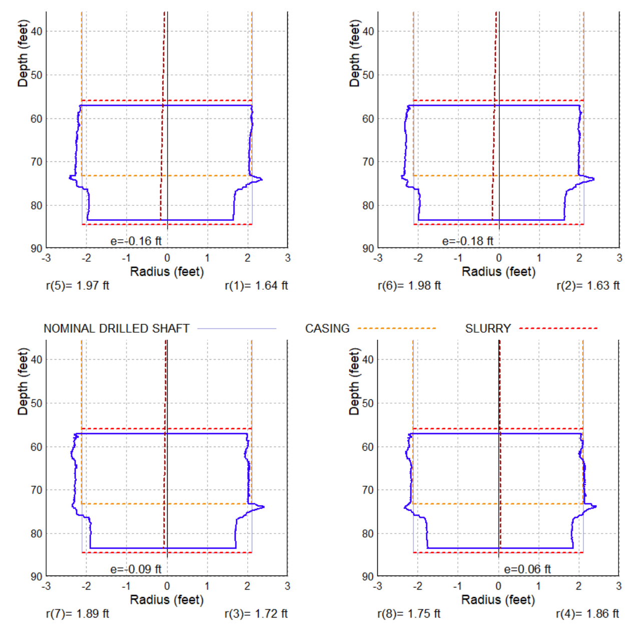

Fig. 6. SHAPE test results from shaft with caving soil below casing.

3.3 Shaft Excavation Base Cleanliness – SQUID

The Shaft Quantitative Inspection Device (SQUID) is the most recent advancement in drilled shaft base cleanliness assessments. The device quickly pins to the drill rig Kelly bar which not only allows the test to be performed quickly but also allows the drilling rig to provide the downward/crowd force required to penetrate harder materials at the excavation base. The device can also be deployed using a weight and crane line or hoist. The typical total time required to complete the standard base cleanliness evaluation tests at the shaft center and at the four orthogonal sides is typically 15 to 30 minutes. The speed of testing is particularly attractive in materials such as shale that can degrade in strength over time.

As shown in Figure 7, the device consists of three cone penetrometers and three displacement plates. It measures the force independently on each of three instrumented penetrometers as they are advanced through the material at the shaft excavation 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 (Piscsalko et al. 2018).

Fig 7. Shaft Quantitative Inspection Device.

The analysis considers two penetration resistance thresholds, one associated with the penetration resistance defining debris, DTH, and the second defining the penetration resistance offered by natural material, PTH. Each penetration resistance threshold is marked with a dashed vertical line in the output plots. Moghaddam et al. (2018) proposed a base cleanliness interpretation criterion using this device with the debris threshold defined as 0.09 kN of penetration resistance and the natural soil penetration resistance defined as 0.71 kN of penetration resistance. These are user defined thresholds so other values can be selected based on specification requirements or local experience. Resistance values less than DTH are associated with very soft materials that will be readily displaced or due to an uneven base condition causing a debris plate to hang atop a grooved or uneven surface. The measured displacement between crossing the DTH and the PTH thresholds is the defined debris thickness. The test results are presented graphically as a force versus displacement plot as well as in tabular form with the numeric value for the debris thickness at each penetrometer location.

In Figure 8a, penetrometer force-displacement results are shown from a test for a drilled shaft bearing in shale bedrock (Hannigan et al. 2021). The shaft excavation had been left open and filled with support fluid for four days prior to the testing. Due to degradation of the shale bedrock over time, over 123.5 mm of displacement occurred between crossing the DTH and PTH thresholds which exceeded the project specification limits. The shaft was subsequently drilled 0.3 m deeper, followed by cleaning with an airlift, and immediate SQUID retesting. The re-test results, shown in Figure 8b, indicated from 11.5 mm to 19.9 mm of debris which was below the project specification limits. It's worth noting that the load applied to the bedrock by penetrometer #3 (blue line) reached as high as 14 kN with no significant displacement indicating sound bedrock.

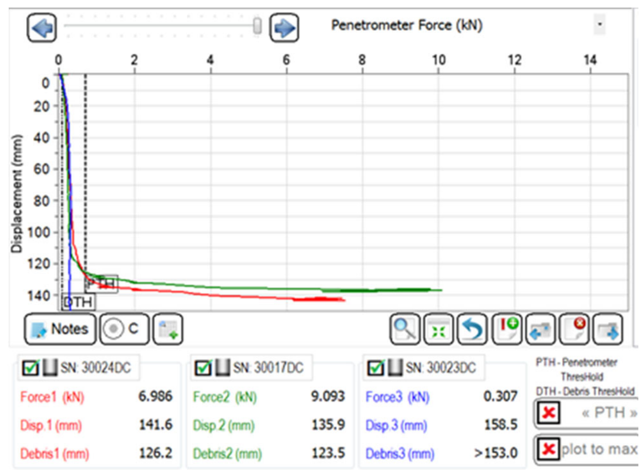

Fig. 8a. SQUID results from shale bedrock exposed to drilling fluid for four days

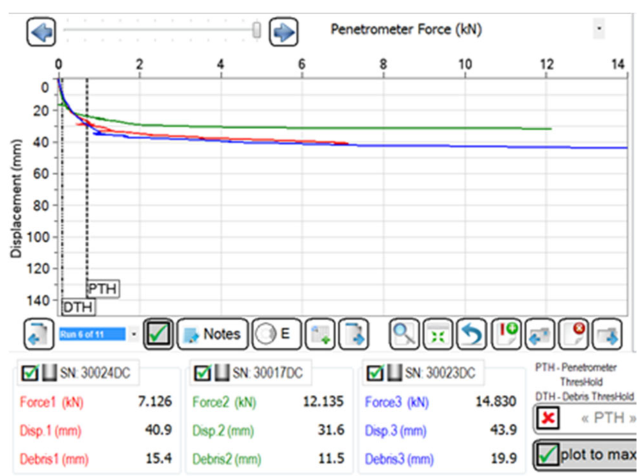

Fig. 8b. SQUID results from shale bedrock re-drilled and cleaned by air lifting

3 BEST PRACTICE AND SPECIFICATION

Experience with these test methods and equipment have provided the authors with opportunities to develop suggestions for successful data collection and testing results.

When deploying the SHAPE device, the device should be as close to the center of the excavation as is practicable. If connected to the Kelly bar of a drill rig, the verticality of the Kelly bar should be closely checked and maintained throughout the data collection process. While neither of these suggestions are absolutely critical for analysis in all cases, they reduce the potential for the SHAPE contacting a side wall and data analysis is often quicker and more reliable. The shaft depth should be measured and a tape measure should be connected to the SHAPE to monitor the depth. This provides the necessary input of the actual test depth and prevents the SHAPE from contacting the bottom of the shaft. It is also important to have fresh water available at the site to rinse the SHAPE after testing when using support fluid such as Bentonite.

When deploying the SQUID using a Kelly bar, the proper Kelly bar adapter should be used and only pinned in place, tightening of the set screws is not recommended. This allows the SQUID some freedom to rotate and increases the probability of all 3 penetrometers contacting the shaft bottom, especially if the shaft bottom is not flat. The SQUID should be lowered to approximately 0.3 meters from the shaft bottom. With the penetrometers zeroed, the operator should slowly lower the SQUID, at approximately 25 mm per second, until contact is made with the shaft bottom and the desired load is applied to the SQUID. The SQUID unit should not be excessively loaded, beyond approximately 40 kN can damage the penetrometers.

When deploying the SQUID using a weight and crane line or hoist, the operator should immediately lift the SQUID once the bottom is encountered. This prevents significant tilting of the SQUID, which may occur if the shaft bottom is not flat and can cause eccentric loading of the penetrometers and possibly damage the unit.

It is critical that SQUID testing be performed just prior to placing concrete as long delays after testing can increase the risk of side wall or bottom of bedrock degradation due to support fluid infiltration, especially when drilling in shale bedrock.

When specifying SHAPE or SQUID testing on a project, several issues should be addressed;

- operator experience requirements
- general test procedures
- equipment calibration frequency
- acceptance criteria (maximum verticality or maximum debris/sediment thickness)
- reporting details

4 CONCLUSIONS

As drilled shafts are increasingly being selected as deep foundation systems due to the large axial and lateral capacities that can be attained, techniques to verify their drilled geometry and base cleanliness have continued to evolve. This paper has provided an overview of two recently developed testing technologies including 1) the SHAPE equipment to measure the geometry of the borehole (shape and verticality) and 2) the SQUID equipment to determine the cleanliness and sediment thickness that may exist at the base of a borehole and qualify the relative hardness of a bedrock when encountered.

This paper also presented case studies for each testing technique where difficulties arose during drilling operations as a result of sidewall cave-in and softening of shale bedrock at the base of the borehole due to water infiltration. Utilizing these two testing technologies provided a timely and cost-effective method to increase quality control and quality assurance.

5 REFERENCES

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