

**QUANTITATIVE ASSESSMENT OF DRILLED SHAFTS BASE-CLEANLINESS USING THE SHAFT
QUANTITATIVE INSPECTION DEVICE (SQUID)**

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ABSTRACT

Shaft base cleanliness is a widely discussed topic regarding quality control and quality assurance of the drilled shafts. Several existing tools and approaches have been proposed and published to assess the shaft base cleanliness. In the drilled shaft construction industry, in situations where the stability of the soil material is questionable, and the groundwater table is shallow, the wet construction method approach is primarily used. In this method, slurry is placed into the hole to maintain stability in the excavation (i.e. drilled hole) and to impede the intrusion of groundwater into the excavation. During the drilling process, cuttings, debris and sediments are accumulated at the bottom of the hole which can impact the performance of the deep foundation element. The bottom of the drilled hole is typically cleaned using an airlift system and/or cleaning buckets to ensure the drilled shafts base cleanliness. After this process is completed, the conditions at the drilled shaft's base can be quantitatively assessed using shaft base inspection devices. This paper presents results of a side-by-side comparison of Mini-SID and Shaft Quantitative Inspection Device (SQUID) tests performed for seven drilled shafts installed in intermediate geomaterial. The effort associated with data collection, debris definition and measurements are presented and discussed in detail.

KEY WORDS: QUANTITATIVE ASSESSMENT, DRILLED SHAFTS, BASE CLEANLINESS, SQUID

INTRODUCTION

After the design process, many factors associated with the construction of drilled shafts have significant impact on the performance of the foundation element. One of the important factors is the shaft base cleanliness prior to placing concrete. Dry and wet excavation procedures are two widely used methods for drilled shaft construction. In situations where the stability of the soil material is questionable, and the groundwater table is shallow, the wet method approach is generally preferred over the dry method. In the wet method, slurry is placed into the hole to maintain stability in the excavation (i.e. drilled hole). During and after the drilling process, cuttings, debris, and sediments are accumulated at the shaft base which can impact the performance of the deep foundation element. To achieve shaft base cleanliness, an airlift system and/or cleaning buckets are used.

The drilled shaft's serviceability and performance could be affected by the accumulation of unsuitable loose material at the shaft's base. Therefore, the shaft base inspection becomes important and at the same time challenging when the wet method is implemented. As part of a quality assurance process, specialized inspection equipment such as the *Miniature* Shaft Inspection Device (Mini-SID) has been used to estimate the shaft base cleanliness. After cleaning out the drilled hole, the device is lowered into the drilled hole using a hoisting system, and several shaft base images are obtained by a camera and are qualitatively analyzed to assess the conditions at the shaft base. This paper presents results from seven drilled shafts inspected for base cleanliness using both the Mini-SID and the Shaft Quantitative Inspection Device (SQUID). The Mini-SID results were qualitatively evaluated from the recorded images of the shaft base conditions. Comparison SQUID results were quantitatively evaluated from the measured force and displacement data collected at the shaft base. Each inspection tool and their associated data collection process are presented, including physical and mechanical aspects. A theoretical description of what is considered to be debris accumulated at the shaft base is presented and discussed. Finally, debris thicknesses obtained from the Mini-SID are compared to those determined using the SQUID.

SHAFT BASE CLEANLINESS

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. 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.

The governing documents published by each DOT were reviewed to summarize current drilled shaft construction practice. This review process consisted of obtaining the latest version of the relevant document, identifying the section addressing shaft base cleanliness, and summarizing the DOT allowed debris thickness limits. The results of this review process are summarized in Table 1. It is important to note that the debris thickness is not addressed as a minimum and maximum thickness. The majority of the DOT specifications require a debris thickness smaller than a certain threshold for 50 percent of the shaft base, and a different maximum limit. Table 1 illustrates these values as lower threshold and upper threshold, respectively.

Table 1. Debris thickness specified by each State Department of Transportation

State	Lower Threshold (in)	Upper Threshold (in)	State	Lower Threshold (in)	Upper Threshold (in)
ALABAMA	0.5	1.5	MONTANA	1	1
ALASKA	0.75	1.5	NEBRASKA	NA	NA
ARIZONA	NA	NA	NEVADA	1	1
ARKANSAS	NA	NA	NEW HAMPSHIRE	NA	NA
CALIFORNIA	NA	NA	NEW JERSEY	0.5	1.5
COLORADO	NA	NA	NEW MEXICO	1	1.5
CONNECTICUT	NA	NA	NEW YORK	NA	NA
DELAWARE	0.5	3	NORTH CAROLINA	0.5	1.5
FLORIDA	0.5	1.5	NORTH DAKOTA	NA	NA
GEORGIA	NA	NA	OHIO	NA	NA
HAWAII	0.5	1.5	OKLAHOMA	0.5	1.5
IDAHO	NA	NA	OREGON	2	6
ILLINOIS	0.5	1.5	PENNSYLVANIA	NA	NA
INDIANA	0.5	1.5	RHODE ISLAND	NA	NA
IOWA	0.5	1	SOUTH CAROLINA	0.5	1.5
KANSAS	0.5	NA	SOUTH DAKOTA	NA	NA
KENTUCKY	NA	0.5	TENNESSEE	0.5	1.5
LOUISIANA	0.5	1.5	TEXAS	NA	NA
MAINE	NA	NA	UTAH	NA	NA
MARYLAND	NA	NA	VERMONT	NA	NA
MASSACHUSETTS	1	3	VIRGINIA	NA	NA
MICHIGAN	0.5	1.5	WASHINGTON	NA	NA
MINNESOTA	NA	NA	WEST VIRGINIA	NA	NA
MISSISSIPPI	0.5	NA	WISCONSIN	0.5	1.5
MISSOURI	0.5	1.5	WYOMING	NA	NA

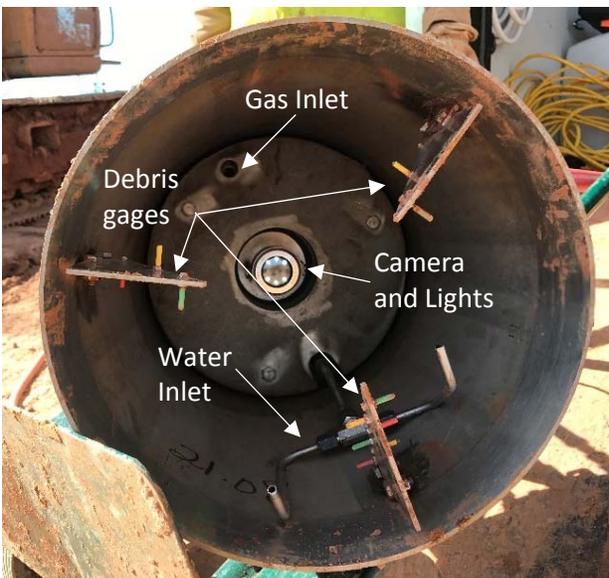
NA = Not Available

Although many DOT specifications did not include a minimum or maximum debris thickness value, the section addressing the shaft base cleanliness often states that the responsible engineer will define the proper debris thicknesses associated with the drilled shaft construction. In other instances, the document simply did not include any section specifically addressing drilled shaft construction procedures.

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, GEC-10, the FHWA drilled shafts manual by Brown et al., (2010) lists the tools commonly available in 2010 for quality assurance purposes including the shaft base cleanliness. The SQUID is not included in this list as it was introduced in 2016.

MINIATURE SHAFT INSPECTION DEVICE (MINI-SID)

One of the base inspection tools listed in the FHWA (2010) is the Miniature Shaft Inspection Device (Mini-SID) which 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, Figure 1a. The test procedure consists of mounting the device on top of the drilled hole and lowering it into the hole by using a winch, Figure 1b. Once the device is located at the bottom of the drilled hole, the compressed gas will displace the slurry out of the diving bell creating a slurry free zone, and a photograph of the shaft base condition can be captured. If the depth gages are covered with slurry or mud, the water inlet is activated to wash off the gages. Images obtained from the shaft base will be analyzed to determine the debris thickness, Figure 2. However, since the Mini-SID results are presented numerically (i.e. Debris Thickness <0.5-in, 0.5-in, ,1.5-in, etc.), a question remains to be answered “is the Mini-SID test a qualitative or quantitative assessment?”.



a) Camera and depth gages on a Mini-SID



b) Mini-SID lowered into the drilled hole

Figure 1. Shaft Inspection Device details

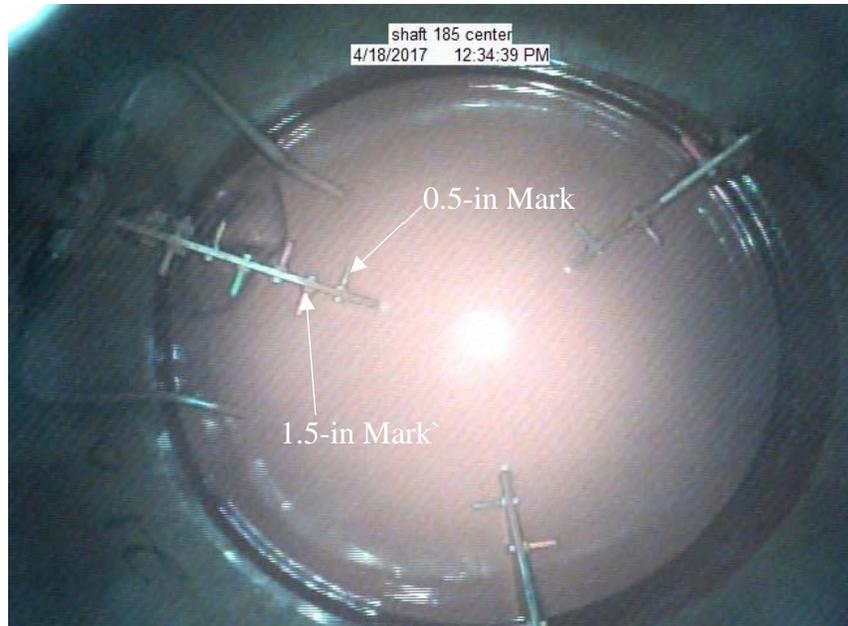


Figure 2. Mini-SID image taken from the shaft base after cleaning the drilled hole

SHAFT QUANTITATIVE INSPECTION DEVICE (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-in² (10-cm²), 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 Device

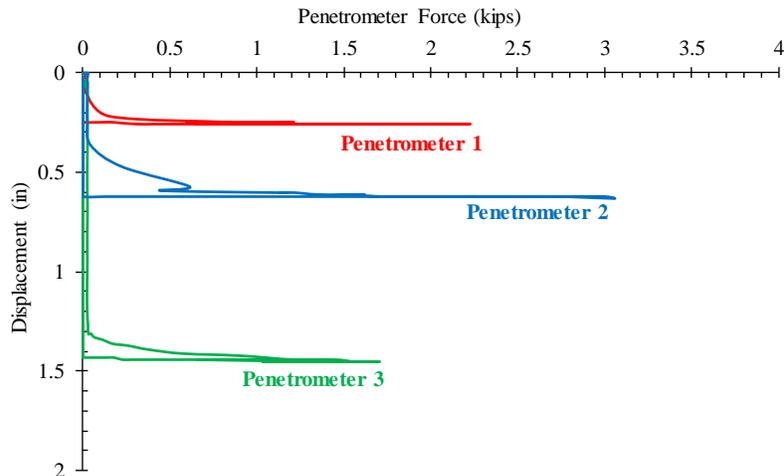


Figure 4. Penetrometer Force and Displacement plot from a SQUID Test

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 2.0-ksf (95-kPa), and a unit weight ranging between 100-pcf (16-kN/m³) and 120-pcf (19-kN/m³). With these strength parameters, and applying the general bearing capacity theory proposed by Terzaghi (1943) for circular foundations, equation (1), the resistance to penetration of a flat tip with a cross section area of 1.55-in² (10-cm²) was determined to be between 0.020-kips (0.089-kN) and 0.160-kips (712-kN).

$$q_{ult} = 1.3s_u N_c \quad (1)$$

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 (704-kN), respectively. Furthermore, it is reasonably assumed that materials with resistance to penetration smaller than 0.020-kips (0.089-kN) will have unit weight smaller than 150-pcf (24kN/m³). Therefore, this softer material will be displaced by the concrete during pouring process. For the upper limit, a material with resistance to penetration force greater than 0.160-kips (704-kN) is considered a natural soil or rock.

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 gradually increases to a maximum registered load for each penetrometer, and returns to zero value as the device is unloaded. Similarly, the displacement plates registered displacements corresponding to each load, and gradually returned to zero when the entire Kelly-Bar weight was removed.

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). This process is automated in the software and the debris thickness is reported graphically and in a tabular form.

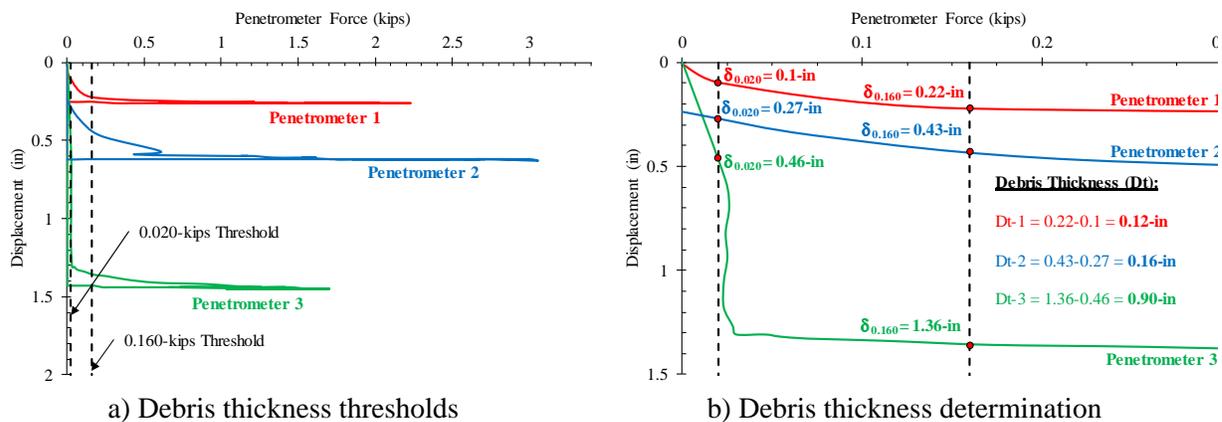


Figure 5. Force-Displacement plots obtained from SQUID testing

DATASET AND DATA ANALYSIS

In an effort associated with data collection for debris thickness determination using force-displacement plots, Mini-SID and SQUID tests were completed side-by-side. For an ongoing project in Oklahoma City, Oklahoma, seven 60-in (1524-mm) diameter drilled shafts were selected, and after cleaning the shaft base both tests were performed at each shaft base within locations identified as center, north, south, east, and west. All drilled shafts pertaining to this project, were designed to be socketed in an Intermediate Geomaterial (IGM) classified as weathered shale. The dataset analyzed for this study consisted of 34 side-by-side test results.

MINI-SID DATA

From a Mini-SID test, the image taken from the shaft base is analyzed visually (i.e. qualitatively) and the term “less than 0.5-inch” is usually used to describe the results when a shaft base meets the project specifications. All images obtained from the test were carefully reviewed, and debris thicknesses were

estimate from a series of photo-analysis. For each location, the shaft base photo was analyzed using the scaling tools to determine the debris thickness corresponding to each individual debris gage, as shown in Figure 6. Note that for the photo corresponding to the drilled shaft #161, the reference scale is the 0.55-in (14-mm) which corresponds to the known distance of 1.4142-in (36-mm).

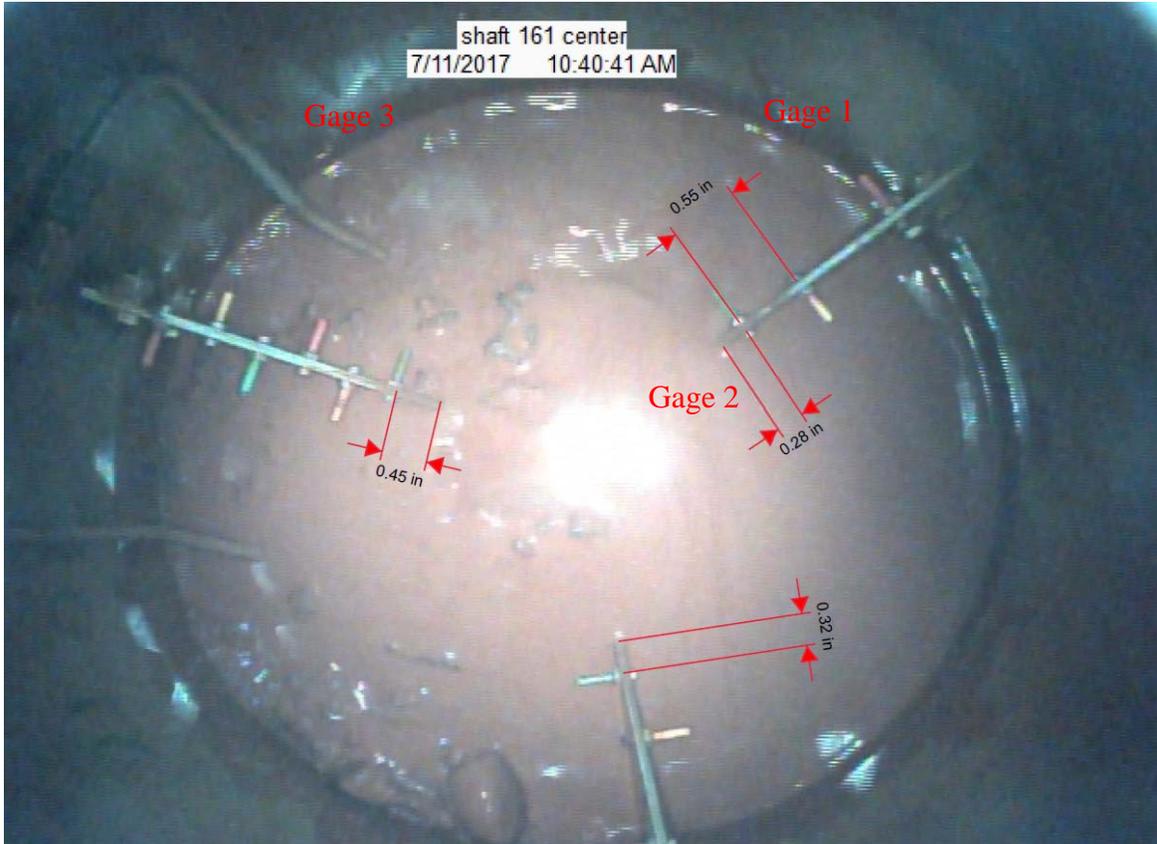


Figure 6. Photo analysis and scaling for debris thickness determination using the Mini-SID

The debris thickness gages consist of color coded pins mounted to 45° angle brackets indicating the debris thickness, as shown in Figure 7. Therefore, after setting the scale based on a known distance (i.e. such as the distance between 0.5-in and 1.5-in gage), the debris thickness can be calculated based on the measurement from the top of the debris to the first pin. This measurement is subtracted from the total distance from the bottom of the debris to the first pin (i.e. the first hypotenuse) and the hypotenuse covered by the debris material is obtained. With the known 45° angle and the debris hypotenuse, the debris thickness can be estimated, as shown in Figure 7. This process was completed for all the locations at which the debris gage and the known distance was visible in the photos taken during the Mini-SID testing. For the drilled shaft #161 at the center location shown in Figure 6, the average debris thickness was 0.247-in (6mm) with individual gage readings of 0.197-in (5mm), 0.226-in (5.7mm), and 0.318-in (8mm) corresponding to gages 1, 2, and 3, respectively.

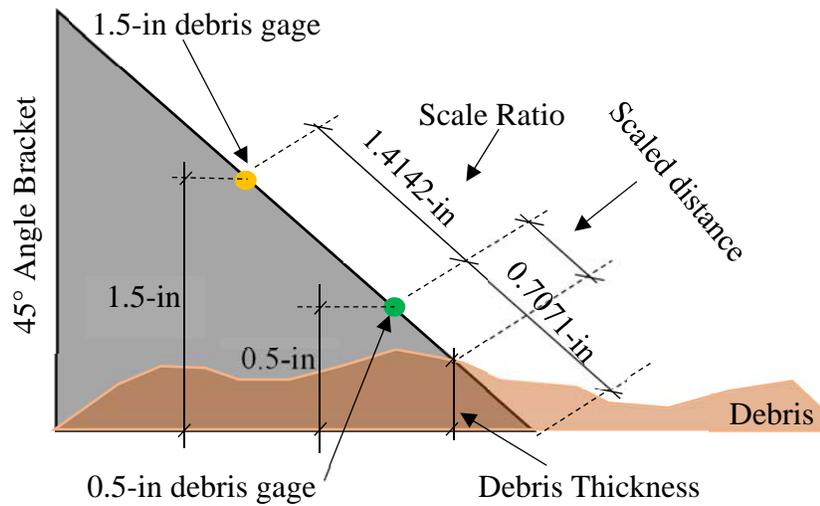


Figure 7. Mini-SID angle bracket details

SQUID DATA

The SQUID test was completed to obtain force versus displacement curves at approximately the same locations where Mini-SID equipment was used. For each shaft, the device was lowered into the drilled hole and once it reached the shaft base the Kelly-Bar was released to transfer its buoyant weight to the device. During this process, the penetrometers measured the strain while the displacement plates measured the penetration distance into the debris material. The force, calculated from the measured strain, was then plotted versus the displacement, as shown in Figure 8. It is important to note that Figure 8 represents the same shaft tested at the same location as shown in Figure 6.

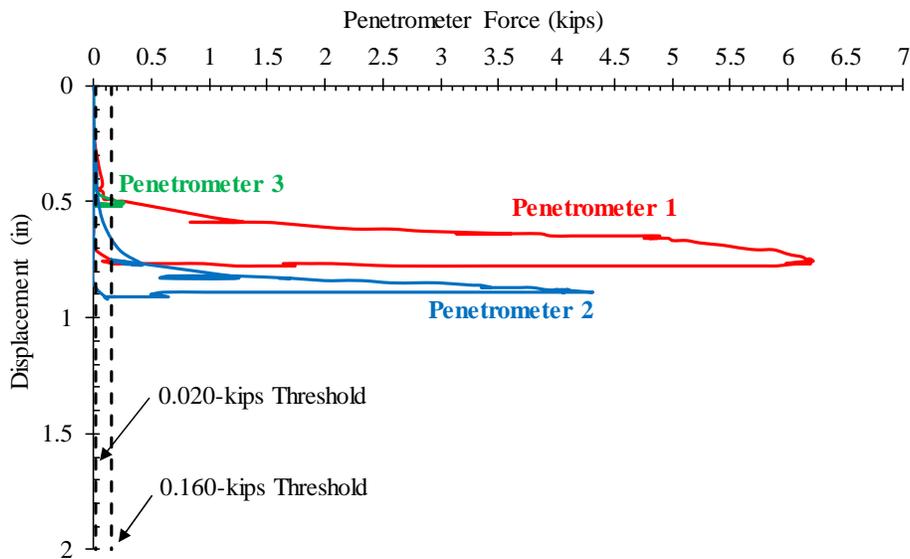


Figure 8. SQUID Test results for Drilled Shaft 161-Center

Using the force-displacement plots and the definition of a debris material, results from the SQUID test shown in Figure 8 indicated an average debris thickness of 0.20-in (5mm) at the center of the shaft with 0.23-in (6mm), 0.04-in (1mm), and 0.33-in (8mm) corresponding to penetrometers 1, 2, and 3, respectively.

In the case of the project presented in this study, the base material tested for debris thickness consisted of an IGM. Analyzing the plot shown in Figure 8, it is noted that the penetrometers travel through a soft material up to a point where an abrupt change in force is observed whereas the displacement change is minimal. This can be interpreted as a sudden encounter of hard material (i.e. IGM) by the penetrometers. As a comparator and to illustrate the force-displacement plot for a material different than the IGM, results obtained from a different project located in North Carolina where the base material consisted of a very dense sand is illustrated by Figure 9. As observed, the penetrometers passed through the debris material at an early stage and, in contrast to the plot shown in Figure 8, a gradual increase of the force with additional displacement is observed instead of the abrupt change in force in the IGM case. The response of penetrometer 3 indicates the existence of a loose sand different than what is defined as a debris at the shaft base, and the penetrometers were able to travel through this material as the displacements increased up to 6-inches (152-mm). However, the average debris thickness is 0.20-in (5-mm), with 0.13-in (3-mm), 0.35-in (9-mm), and 0.13-in(3-mm) of displacements for penetrometers 1, 2, and 3, respectively.

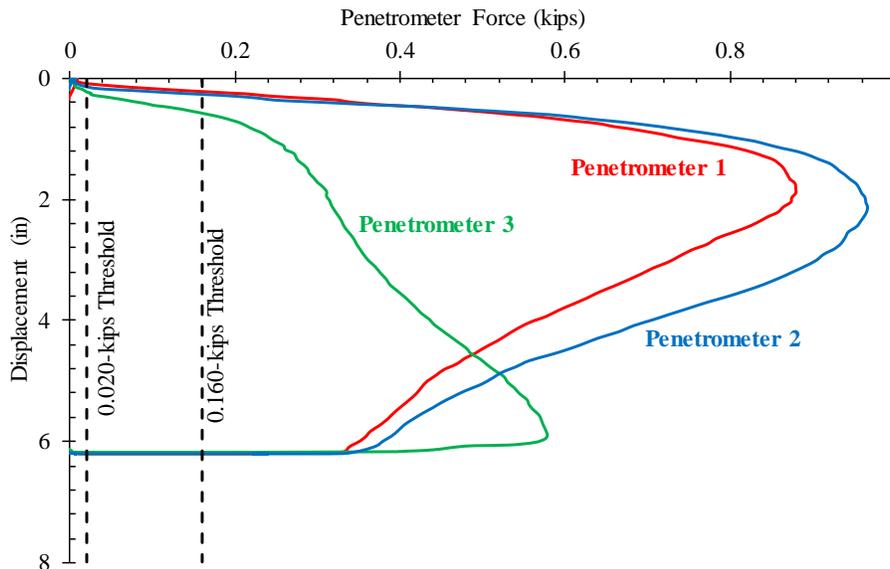


Figure 9. SQUID test data corresponding to dense sand material at the shaft base

RESULTS

From the side-by-side tests 34 data points corresponding to debris thickness determined by the two different methods were analyzed. These results were plotted to observe the relationship between the two methods as shown in Figure 10. The solid line represents the predictive model passing through the origin with an R-Square value of 57%. Several factors such as the photo analysis where the debris thickness for the Mini-SID data was determined using scaling tools, the quality of the photos taken at the shaft base, and not being at precisely the same locations, among others, could influence the debris thickness determination and further create a scatter in the data. However, according to the project specifications, the shaft base has to be cleaned in a way that 50 percent of each shaft base has less than 0.5-in (12mm) of debris and the remaining 50 percent has no greater than 1.5-in (38mm) of debris. Based on results from either method, the shaft base cleanliness was satisfactory within the requirements in the project specifications indicating that the readings from either specialized equipment are consistent.

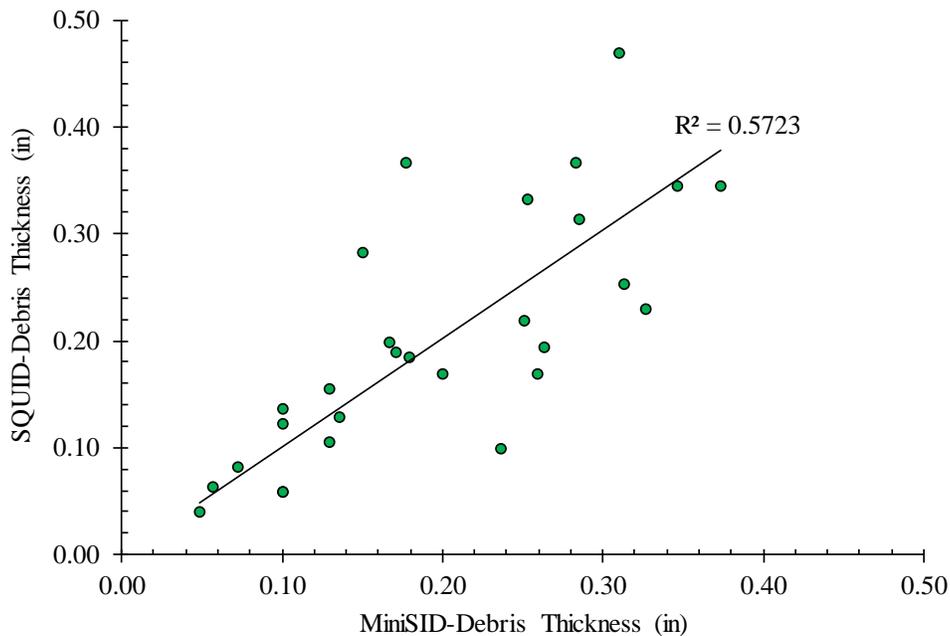


Figure 10. Scatter plot for the Mini-SID Vs. SQUID debris thickness

SUMMARY AND CONCLUSIONS

This paper presents a side-by-side comparison between debris thickness determined from two different shaft base cleanliness inspection devices: Mini-SID and SQUID. The first device estimates the debris thickness based on extrapolations from three gages with color coded pins representing different thicknesses. The shaft base cleanliness is estimated from photos taken from the shaft base and the debris thickness is determined based on a qualitative assessment. In case of the SQUID, the debris thickness is determined based on forces measured with three penetrometers and three displacement plates. The force is plotted versus displacement for each penetrometer. For comparison purposes, the arithmetic average of debris thickness determined from the three gages of the Mini-SID and from the three penetrometers of the SQUID were used.

The relationship between the debris thickness from Mini-SID and the debris thickness from SQUID was studied and a predictive model with R-Square of 57% was developed. The observed data scatter can be attributed to the differences in the two methods. In one test, the debris thickness is estimated from a scaled projection of visually observed pins, while in the other test the thickness is determined from the difference between upper and lower thresholds. There is great similarity in results, and particularly considering the tests were conducted at likely slightly different locations at the shaft base.

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REFERENCES

- ALDOT (2012) *Standard Specifications for Highway Construction*. Alabama Department of Transportation Bridge Bureau
- AKDOT (2017) *Standard Specification for Highway Construction*, Alaska Department of Transportation
- AZDOT (2011) *Bridge Design Guidelines*, Arizona Department of Transportation
- ARHTD (2017) *Standard Specification for Highway Construction*. Arkansas State Highway and Transportation Department
- Brown, D. A., Turner, J. P., & Castelli, R. J. (2010) *Drilled shafts: Construction procedures and LRFD design methods*. US Department of Transportation, Federal Highway Administration.
- CALTRANS (2015) *Standard Specification*, California State Transportation Agency
- CODOT (2011) *Standard Specifications for Road and Bridge Construction*, Colorado Department of Transportation
- CTDOT (2005) *Standard Specifications for Roads, Bridges and Incidental Construction*. Connecticut Department of Transportation
- DEDOT (2016) *Standard Specifications for Road and Bridge Construction*, The State of Delaware Department of Transportation.
- FDOT (2016) *Standard Specifications for Road and Bridge Construction*. Florida Department of Transportation
- GDOT (2013) *Standard Specifications for Road and Bridge Construction*, Georgia Department of Transportation
- HDOT (2005) *Standard Specifications, Section 511*, State of Hawaii Department of Transportation
- IDTD (2017) *Standard Specifications for Highway Construction*, Idaho Transportation Department
- ILDOT (2016) *Standard Specifications for Road and Bridge Construction*, Illinois Department of Transportation
- INDOT (2016) *Standard Specifications*, Indiana Department of Transportation
- IADOT (2012) *Standard Specifications for Highway and Bridge Construction*, Iowa Department of Transportation
- KSDOT (2015) *Standard Specification for State Road and Bridge Construction*, Kansas Department of Transportation
- KYTC (2012) *Standard Specifications for Road and Bridge Construction* Kentucky Transportation Cabinet
- MEDOT (2014) *Standard Specifications*, The Maine Department of Transportation
- MADOT (2013) *Standard Specifications for Highway and Bridges* Massachusetts Department of Transportation
- MIDOT (2011) *Standard Specifications for Construction*, Michigan Department of Transportation
- MSDOT (2017) *Standard Specifications*, Mississippi Department of Transportation

MODOT (2016) *Standard Specifications for Highway Construction*, Missouri Department of Transportation

MTDT (2014) *Standard Specifications*, Montana Department of Transportation

NEDOT (2007) *Standard Specifications for Highway Construction* Nebraska Department of Transportation

NVDOT (2014) *Standard Specifications for Road and Bridge Construction*, Nevada Department of Transportation

NHDOT (2016) *Standard Specifications for Road and Bridge Construction*. State of New Hampshire Department of Transportation.

NJDOT (2007) *Standard Specifications for Road and Bridge Construction*, New Jersey Department of Transportation

NMDOT (2014) *Standard Specifications for Highway Construction*, New Mexico Department of Transportation

NYDOT (2016) *Standard Specifications for Highway Construction*, New Mexico Department of Transportation

NCDOT (2012) *Standard Specifications for Road and Structures*, North Carolina Department of Transportation

NDDOT (2014) *Standard Specifications for Road and Bridge Construction* North Dakota Department of Transportation

OHDOT (2016) *Construction and Material Specifications*, State of Ohio Department of Transportation

OKDOT (2009) *Standard and Specifications Book*, Oklahoma Department of Transportation

ORDOT (2015) *Standard Specification for Construction*, Oregon Department of Transportation

PADOT (2016) *Standard Specifications* Pennsylvania Department of Transportation

RIDOT (2007). *LRFD Bridge Design Manual*. Rhode Island Department of Transportation

SCDOT (2007) *Standard Specifications for Highway Construction*, South Carolina Department of Transportation

SDDOT (2015) *Standard Specifications for Roads and Bridges*. South Dakota Department of Transportation

Terzaghi, K. (1943). *Theoretical soil mechanics* (Vol. 18). New York: Wiley

TNDOT (2015) *Standard Specifications for Road and Bridge Construction*, Tennessee Department of Transportation

TXDOT (2014) *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges*, Texas Department of Transportation

UTDOT (2017) *Standard Specifications for Road and Bridge Construction*, Utah Department of Transportation

VTDOT (2011) *Standard Specifications for Construction*, Vermont Agency of Transportation

VADOT (2010) *Road and Bridge Specifications*, Virginia Department of Transportation

WSDOT (2015) *Standard Specifications for Road, Bridge, and Municipal Construction*, Washington State Department of Transportation

WVDOH (2010) *Standard Specifications: Road and Bridges*, West Virginia Division of Highways

WIDOT (2017) *Standard Specification* State of Wisconsin Department of Transportation

WYDOT (2010) *Standard Specifications for Road and Bridge Construction*, Wyoming Department of Transportation