Use and Comparison of New QA/QC Technologies in a Test Shaft

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ABSTRACT

Drilled shafts are increasingly being used for foundation support. The quality of the constructed foundation is critical due the heavy foundation loads and limited redundancy of many drilled shaft foundations. On a recent project in the United States, several traditional and newer methods of quality control and quality assurance were used to assess the drilled shaft excavation, base condition, concrete quality, and capacity. The radii, shape, verticality, and volume of the drilled shaft excavation was evaluated with a SHaft Area Profile Evaluator (SHAPE), and the cleanliness of the shaft base prior to concrete placement was assessed with a Shaft Quantitative Inspection Device (SQUID). The placed concrete quality was evaluated with Cross-hole Sonic Logging (CSL) as well as Thermal Integrity Profiling (TIP). Finally, a bi-directional static load test (BDSLT) was conducted on the test shaft to determine the shaft capacity.

This paper will provide a brief review of the QA/QC tests and their results. In addition, the constructed shaft quality information available from similar methods will be compared and discussed including advantages and disadvantages of the respective methods.

INTRODUCTION

On drilled shaft projects in the U.S., a trial shaft and/or a test shaft is often specified to check the proposed shaft installation methods before proceeding into production. These trial or test shafts typically require quality assurance tests for base cleanliness, verticality, and concrete quality during construction. Trial shafts are used to evaluate the contractor's means and methods and are not statically loaded tested. A test shaft typically includes a conventional top-down or, more frequently, a bi-directional jack assembly so that the load carrying capacity can be assessed in additional to the other quality assurance tests.

Base cleanliness requirements vary depending upon the design and expected load transfer mechanism, the bearing materials, and whether the shaft was completed using wet or dry construction methods. The U.S. Federal Highway Administration guide specification for drilled shafts, Brown et al., (2018), limits sediment and debris thickness for wet or dry shafts in rock to less than 13 mm (0.5 inches) over 50% of the base area. For shafts on soil, the sediment and debris thickness is limited to less than 75 mm (3 inches) for wet construction, and less than 37 mm (1.5 inches) for dry construction.

More restrictive base cleanliness criteria are frequently specified when the shaft is expected to carry a large portion of the applied load through base resistance. In these cases, the average thickness of sediment is limited to 13 mm over 50% of the base area with no portion of the base having more than 37 mm (1.5 inches) of debris. Base cleanliness criteria are enforced for confirmation of base resistance and settlement considerations as well as to minimize possibility of concrete contamination from debris.

Shaft verticality or plumbness is often specified to be within 1.5% of plumb in soil and within 2.0% of plumb in rock, AASHTO (2017), Brown et al., (2018). Plumbness is measured from the top of shaft or from the mudline, whichever is lower.

The as-constructed quality and integrity of drilled shaft concrete is typically assessed through concrete volume plots versus elevation, cross-hole sonic logging test results, or thermal integrity profiling. Concrete volume versus elevation plots are described in Brown et al., (2018), guidance on evaluating integrity test results is available in an industry authored document for cross-hole sonic logging results by the Deep Foundations Institute (2019), and for thermal integrity profiling in Piscsalko et al., (2016). Guidance from these documents will be referred to later in this document.

TEST SHAFT DETAILS

At the test shaft location, the general subsurface conditions consist of very loose silty fine sand (SM) to very soft sandy clay (CH) to a depth of 16.1 m (53 ft). These materials were underlain by a marl layer consisting of very loose to medium dense silty sand (SM) to clayey sand (SC) to a depth of 20.3 m (66.7 ft). The marl layer was in turn underlain by a limestone formation comprised of loose to medium dense silty fine sand (SM) with occasional strongly cemented sand layers. The test shaft was terminated in this limestone formation.

The test shaft was constructed by first vibrating a 22.3 m (73 ft) steel casing to a depth of 18.6 m (60.9 ft) below grade. The casing was 2,490 mm O.D. x 16 mm wall (98 in x 5/8 in). A 2,390 mm O.D. (94 in) Double Open Dirt Drilling Bucket, shown in Figure 1, was used to complete the shaft excavation to its' final depth of 32.6 m (106.9 ft). Polymer slurry was used to maintain an open excavation through the uncased zone. Bottom cleaning was performed with this drilling bucket after the auger teeth plate was removed forming a flat bottom cleanout bucket. After cleanout, a full-length, 2,083 mm O.D (82 in) reinforcing cage was installed in the shaft. Concrete, with a design slump of 203 mm (8 in) was then pumped and placed in the shaft via a 254 mm I.D. (10 in) tremie pipe. The final shaft base was at Elevation -32.01 m (-105.0 ft) and the final top of shaft concrete was at Elevation +1.19 m (+3.9 ft).

TEST SHAFT QA/QC

Shaft Area Profile Evaluator

A SHaft Area Profile Evaluator or SHAPE device was used to determine the characteristics of the wet pour, drilled shaft excavation. The device was pin connected to the drill rig Kelly bar and then lowered into and retrieved from the shaft excavation. While in the wet excavation, this device used eight ultra-sonic pulsers to scan the side walls at a rate of approximately one scan per second. It provided a quick check of the excavation verticality, radii, shape, and drilled hole volume. The test was performed a few hours before inserting the reinforcing cage in the hole. A photograph of the device prior to insertion into the test shaft is provided in Figure 2. Test results, presented in Figures 9 and 10, are discussed later in this document.

Shaft Quantitative Inspection Device

A Shaft QUantitative Inspection Device or SQUID was used to check the base cleanliness two hours prior to placing the reinforcing cage and initiating the concrete pour. This device used three 10 cm^2 (1.55 in^2) cone penetrometers and three 521 mm (6 in) displacement plates to assess base cleanliness. For the purpose of sediment thickness measurements, flat tips were attached to the penetrometers for the testing. A photograph of the device prior to lowering it into the test shaft is provided in Figure 3. Base cleanliness tests were performed in the center of the shaft as well as in North, East, and West quadrants of the shaft. The South quadrant test was not performed due to limitations on the drill rig reach. The SQUID was pushed into the base material by the weight of the drill rig Kelly bar. The device penetrometers can be pushed to a maximum penetrometer pressure of 100 MPa (14 ksi). Test results are presented in Figures 11 and 12, with test result discussion provided later in this paper.

Bi-Directional Static Load Testing

Three 6.7 MN (750 ton) capacity GRL-Cells were used in the bi-directional jack assembly. This multi-cell jack assembly was located 4.2 meters (13.8 ft) above the shaft base elevation. The jack-assembly was capable of producing a 20 MN (2,250 ton) jack load and a maximum bi-directional test load of 40 MN (4,500 tons). A photograph of the bi-directional jack assembly prior to insertion in the test shaft is provided in Figure 4. Bi-directional test results are presented in Figures 13, 14, and 15 with discussion presented later in this paper.

Cross-hole Sonic Logging

Access tubes for cross-hole sonic logging were attached to the reinforcing cage at 300 mm (12 in) spacings around the interior of the reinforcing cage. The 38 mm (1.5 in) O.D. steel access tubes ran the full length of the cage, and were pre-cut at the location of the bi-directional jack assembly. The cut access tubes were fitted with expandable couplers at the jack assembly location to accommodate jack expansion. Figure 5 contains a photograph of cross-hole sonic logging being performed on the test shaft. Four profiles were collected and processed concurrently with the CHAMP-Q cross-hole sonic logging system. The multiple transceivers were pulled upwards from the bottom of the CSL access tubes with ultrasonic signals acquired at 50 mm (2 in) vertical intervals as the four transceivers were concurrently raised.

The steel cross-hole sonic logging access tubes are shown attached to the interior of the reinforcing cage in Figure 6. The expandable couplers used on the CSL tubes at the location of the bi-directional cells are visible in the bi-directional jack assembly photograph in Figure 4. CSL test results are presented in Figures 16 and 17, with discussion of the test results provided in a subsequent section of this paper.

Thermal Integrity Profiling

Thermal Integrity Profiling cables were attached to the reinforcing cage at 300 mm (12 in) spacings around the interior of the reinforcing cage. Each individual thermal wire cable had thermal sensors spaced 300 mm (12 in) apart along the length of the cable. The thermal wire cables ran the full length of the reinforcing cage with slack provided at the bi-directional jack assembly location. Figure 6 illustrates the thermal wire being attached to the reinforcing cage.

Immediately after completion of the concrete pour, one Thermal Aggregator (TAG) and seven Thermal Acquisition Ports (TAP-Edge) data logging units were attached to the thermal wire cables. Every 15 minutes, the temperature of each thermal sensor was read by the data loggers. The collected thermal readings from each wire were pushed to the Cloud where they could be viewed in real time. The shaft reached its' peak temperature approximately 26.3 hours after the start of the concrete pour. The thermal integrity profiling results are presented in Figures 19, 20, and 21, with test results discussed later in this paper.

Concrete Placement

During concrete placement, measurements to the top of concrete in the excavation along with the volume of concrete placed were recorded. The concrete volume in both the tremie pipe and the pump lines was subtracted from the concrete volume placed.

QA/QC TEST RESULTS

Excavated Volume

The volume of the shaft excavation has historically been determined post-pour based on the amount of concrete placed in the shaft. The placed concrete volume can be plotted versus depth by measuring the depth to the top of concrete following discharge of each concrete truck and its associated concrete volume from batch plant tickets. The plot of concrete volume versus depth is routinely compared to the theoretical volume versus depth to assess potential integrity issues. A sudden increase in concrete volume compared to the theoretical volume at a given depth is indicative of an oversized shaft due to a bulge or cavity filling. Conversely, a sudden decrease in concrete volume compared to the theoretical volume at a given depth is indicative of an undersized shaft due to an inclusion or necking.

Figure 7 presents a plot of the placed concrete volume versus depth. This figure also includes the theoretical shaft excavation volume versus depth. SHAPE results of the excavated hole volume are also included in this figure. The SHAPE results closely mirror the theoretical volume which appears reasonable given that 58% of the shaft length was permanently cased. Construction concreting records indicate the placed volume was 104% of the theoretical volume. Based on the shaft construction techniques, this implies the extra concrete volume should be located in the lower uncased portion of the shaft.

Shaft Diameter

The average radius and diameter of the constructed shaft was calculated from three methods; the placed concrete volume versus depth, the SHAPE results, and the thermal integrity profiling results. A comparison of the average shaft diameter from these methods as well as with the theoretical shaft diameter versus depth is presented in Figure 8.

The concrete volume information yields the largest shaft diameter below Elevation -22 m (-72 ft) in the uncased portion of the shaft. The concrete volume information also yields the largest shaft diameter above Elevation -4 m (-13 ft) in the permanently cased portion of the shaft which is unreasonable. The shaft diameter calculated by thermal integrity profiling clearly shows the bi-direction jack assembly at Elevation -27.7 m (91.0 ft) due to the heat sink associated with the steel cells at that location. Above Elevation -10.0 m (32.8 ft), the shaft diameter indicated by the thermal integrity profiling is slightly greater than the diameter of the permanent casing. The shaft diameter calculated by SHAPE appears to be the most realistic representation of the constructed shaft.

Verticality

The project specifications required the shaft verticality to not deviate from the plan alignment by more than 6.4 mm (¼ in) per 304.8 mm (1 ft) of depth or 2%. Hence, for the 33.2 m (108.9 ft) long test shaft, the maximum allowable deviation would be 0.69 m (2.26 ft) at the base. Figure 9 presents the SHAPE scan results from the each of four profiles. Note that the depth scale in the scan results is referenced to the top of the drilling slurry at Elevation +3.05 m (+10.0 ft).

As indicated in the profile schematic, sensor 1 is positioned to the north to conduct the test. The four scan profiles indicate the drilled shaft base drifts slightly towards the west. Figure 10 presents the SHAPE determined verticality and eccentricity. The verticality of 0.20% based on a base eccentricity of 0.07 m (0.23 ft) is well within the above noted specification limits. The lower portion of Figure 10 also displays the calculated encroachment area of 0.16 m^2 (1.72 ft^2) into the shaft sidewall.

Base Cleanliness

The project specifications stipulated that less than 13 mm (0.5 in) of sediment or debris be present over a maximum of 50% of the shaft base area at the time of concrete placement. In addition, the maximum sediment or debris present at any location on the base was required to be less than 38 mm (1.5 in).

Figures 11 and 12 present the SQUID test results from four test locations; Center, North, East, and West. Since the primary purpose of the tests were to evaluate base cleanliness, the penetrometers were fitted with a flat tip rather than the conventional cone tip. Base cleanliness was assessed according to the criteria proposed by Moghaddam et al., (2017). The first vertical line, labeled DTH, is associated with penetration resistance associated with debris. 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 second vertical line, labeled PTH, corresponds to the penetration resistance offered by natural soils. The measured displacement between crossing the DTH and PTH thresholds is the defined debris thickness.

The test results in Figures 11 and 12 indicate the debris thickness is typically on the order of 5 mm (0.2 in) or less across the test locations. Two of the eleven penetrometer locations had slightly greater debris thicknesses of 11.8 and 10.3 mm (0.5 and 0.4 in). However, the 13 mm (0.5 in) debris limit was not exceeded at any location. Therefore, less than 50% of the tested shaft base area had less than 13 mm (0.5 inches) of debris and no reading indicated more than the maximum allowed debris thickness at any location of 38 mm (1.5 in). Hence, the test shaft base was very clean.

Geotechnical Design and Capacity

Based on the geotechnical design calculations, the test shaft had an estimated nominal resistance of 20.6 MN (4630 kips). The test shaft was expected to carry approximately 71%

of this nominal resistance or 14.6 MN (3287 kips) in shaft resistance and the remaining 6.0 MN (1348 kips) at the shaft base. The pretest unit base resistance was therefore anticipated by the foundation designer to be 1.34 MPa (28 ksf).

BDSLT results are presented in Figure 13 with the resulting internal force profiles presented in Figure 14. As noted earlier, the test shaft had an anticipated nominal resistance of 20.6 MN (4630 kips) with 14.6 MN (3287 kips) in shaft resistance and 6.0 MN (1348 kips) at the shaft base. The BDSLT results indicate the test shaft had a substantially greater nominal resistance of 34.4 MN (7733 kips) with 26.2 MN (5890 kips) of shaft resistance and 8.2 MN (1843 kips) of base resistance. Hence, test results confirmed the test shaft met the foundation design requirements and further design optimization could be achieved by shortening production shaft lengths.

Unit Base Resistance

The FHWA drilled shaft design manual, Brown et al., (2018), also includes a design procedure for unit base resistance in cohesionless materials using Standard Penetration Test (SPT) N_{60} values. The SPT N_{60} value within 2 diameters below the shaft base elevation ranged from 10 to 20 and had an average value of 13. According to the SPT design procedure in the FHWA manual, the unit end bearing resistance would be 0.75 MPa (15.6 ksf) at a displacement of 5% of the base diameter. The unit base resistance from this design method is less than the geotechnical designer's anticipated unit base resistance.

The unit base resistance was calculated from the bi-directional static load test (BDSLT) result internal force profile in Figure 14 by assuming the foundation segment between the lowest strain gage level and the shaft base had the same unit shaft resistance as the overlying segment. This calculated unit base resistance was greater than both the geotechnical designer's method and the FHWA SPT method unit base resistances noted above. It should be noted that a base displacement of 119 mm (4.7 in) corresponding to 5% of the base diameter was not achieved in the bi-directional static load test. The maximum unit base resistance determined from the BDSLT, presented in Figure 15, was 1.77 MPa (37 ksf) at a displacement of 2.5% of the base diameter.

SQUID penetrometers have a maximum penetration distance into the base material of 150 mm (6 inches). Even with this limited penetration depth, the penetrometer force versus displacement results indicated geotechnical failure occurred between 1.8 to 2.1 MPa (37 to 44 ksf). Geotechnical failure was defined as the break point in the unit resistance versus displacement plots in Figures 11 and 12. In the base materials at this site, the break point was within 20% of the unit end bearing result from the bi-directional test. Obviously, the zone of influence of the 10 cm^2 (1.44 in^2) penetrometer and the 2.4 m (94 in) diameter shaft are significantly different. Therefore, unit base resistance correlations are anticipated to be meaningful only when a uniform material exists within the zone of influence beneath the shaft base.

Concrete Quality and Cover

The test shaft was cast with eight CSL access tubes uniformly spaced around the interior of the reinforcing cage. This resulted in a total of 28 possible CSL profiles from the various tube combinations. A representative selection of CSL profiles is presented in Figures 16 and 17. Each ultrasonic CSL profile consists of two graphs. The left-hand graph for a given profile presents a plot of the first arrival time of the received ultrasonic signal at each sampling depth. The left-hand plot also displays the calculated relative energy of the received signal at each sampling depth. Delays in the first arrival time and/or decreases in the received signal energy are indicative of anomalies in the shaft concrete. The right-hand plot for a given profile stacks the modulated raw data signals to create a "waterfall" diagram. Note that the depth scale in the CSL results is referenced to the top of shaft concrete at Elevation +1.19 m (+3.9 ft).

The shaft concrete quality was assessed in accordance with the evaluation criteria proposed by the Deep Foundation Institute task force on cross-hole sonic logging, Sellountou et al., (2019). The task force proposed CSL rating criteria, presented in Figure 18, identifies highly abnormal CSL results as Class C having a First Arrival Time (FAT) increase of more than 30% or with a FAT increase of 15% and a relative energy reduction greater than 12 dB. Several profiles passing through the bi-directional jack assembly were classified as highly abnormal. However, this result in the jack assembly zone was expected and this it is not indicative of a shaft anomaly. The only profile with a highly abnormal CSL result was perimeter Profile 2-3 which had a FAT delay of 81% near Elevation -17.91 m. This elevation is just below the bottom of the permanent casing. The anomaly was not indicated in any other CSL profiles suggesting its' areal extent was a small portion of the shaft cross sectional area.

The shaft concrete quality was also assessed used Thermal Integrity Profiling (TIP) and evaluation criteria proposed by Piscsalko et al., (2016). The test shaft was cast with eight Thermal Wire Cables uniformly spaced around the interior of the reinforcing cage. A plot of the temperature versus elevation 26 hours and 3 minutes after pour completion is presented in Figure 19.

Unlike the CSL testing which was performed one week after casting, the shaft concrete quality from the TIP data can readily be assessed between ½ peak and peak temperature, or 13 to 26 hours. The average temperature data versus elevation in Figure 19 indicates a relatively uniform shaft. The temperature roll-off at the shaft top and bottom conditions are normal. The only significant variation in average temperature occurs at the location of the bi-directional jack assembly which is to be expected. Hence, no significant anomalies are indicated in the shaft. The 12 degree Centigrade range in diametrically opposite thermal wires that occurs near Elevation -14 to -15 m (-46 to -49 ft) indicates shifting of the reinforcing cage. Thermal wires 1, 2 and 8 have the hottest temperatures and thermal wires 4, 5, and 6 have the coolest temperatures in this region. This indicates the northern portion of the cage (wires 1, 2, and 8) is shifted towards the center of the shaft and the southern portion of the cage (wires 4, 5, and 6) is shifted towards the soil.

Thermal wires 2 and 3 correspond to CSL access tubes 2 and 3. The CSL results indicated a significant anomaly in Profile 2-3 near Elevation -17.91 m (-58.8 ft) with a FAT delay of 81%. Thermal wires 2 and 3 do not indicate any anomalies near this elevation and, as noted above, are actually shifted towards the center of the shaft. Piscsalko et al., (2016) proposed a criterion that evaluated thermal integrity profiling results based on the structural and geotechnical impact of an anomaly. According to this criterion, a shaft was considered satisfactory if the effective average radius reduction was 0 to 6% and the local cover criteria was met. An anomaly was indicated if the thermal integrity profiling results had an effective average radius reduction greater than 6% and the local cover criteria was not met. Based on this criterion, the test shaft would be acceptable as the effective average radius reduction did not exceed 6% and a concrete cover criterion was not specified.

A plot of the radius and concrete cover versus elevation is presented in Figure 20. The calculated average shaft radius is greater than required shaft radius throughout except were affected by the GRL-Cells. Similarly, the average concrete cover is 150 mm (3 in) or greater. Note that the cage shifting previously described results in a concrete cover on the order of 100 mm (2 in) in the vicinity of wires 5 and 6 from Elevation -14 to -26 m (-46 to -85 ft). A three-dimensional depiction of the shaft with an overlay of the reinforcing cage is presented in in Figure 21. This figures also includes a generalized soil profile.

CONCLUSIONS

Several benefits were obtained from the installation and QA/QC testing of a test shaft on the project prior to production shaft installation. The test shaft QA/QC tests confirmed that the contractor's means and methods of shaft installation resulted in a shaft meeting verticality, base cleanliness, concrete quality and integrity requirements. The bi-directional static load test confirmed that the design was achievable and that further optimization of shaft lengths were possible.

The SQUID testing of the shaft base condition indicated the presence of minimal debris and a very clean shaft base. Bi-directional static load test results indicated a greater unit base resistance than used in the design as well as that indicated by a frequently used design method. A promising correlation between SQUID penetration resistance and unit base resistance was also obtained for the base materials tested.

The shaft verticality and base cleanliness were quickly checked by the SHAPE and SQUID equipment, respectively prior to shaft concrete placement. These devices showed the benefit of newer technology in shaft construction and quality control.

The shaft concrete quality of the 2.38 m (7.83 ft) diameter drilled shaft was evaluated by cross-hole sonic logging (CSL) seven days after concrete placement and by thermal integrity profiling (TIP) one day after concrete placement. Both methods indicated a high-quality shaft. The localized highly abnormal CSL result was not apparent in the corresponding TIP results. The anomaly was therefore considered insignificant based on the thermal integrity profiling results. A significant reduction in the time required for shaft acceptance is possible with TIP as the test results were available 6 days earlier than the CSL results.

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Figure 1. Double Open Drilling Bucket.

Figure 2. Shaft Area Profile Evaluator.

Figure 3. Shaft Quantitative Inspection Device.

Figure 4. 20 MN Bi-Directional Jack Assembly Attached to the Reinforcing Cage.

Figure 5. Cross-hole Sonic Logging Test Using Multiple Transceivers.

Figure 6. Thermal Integrity Profiling Wire Attachment.

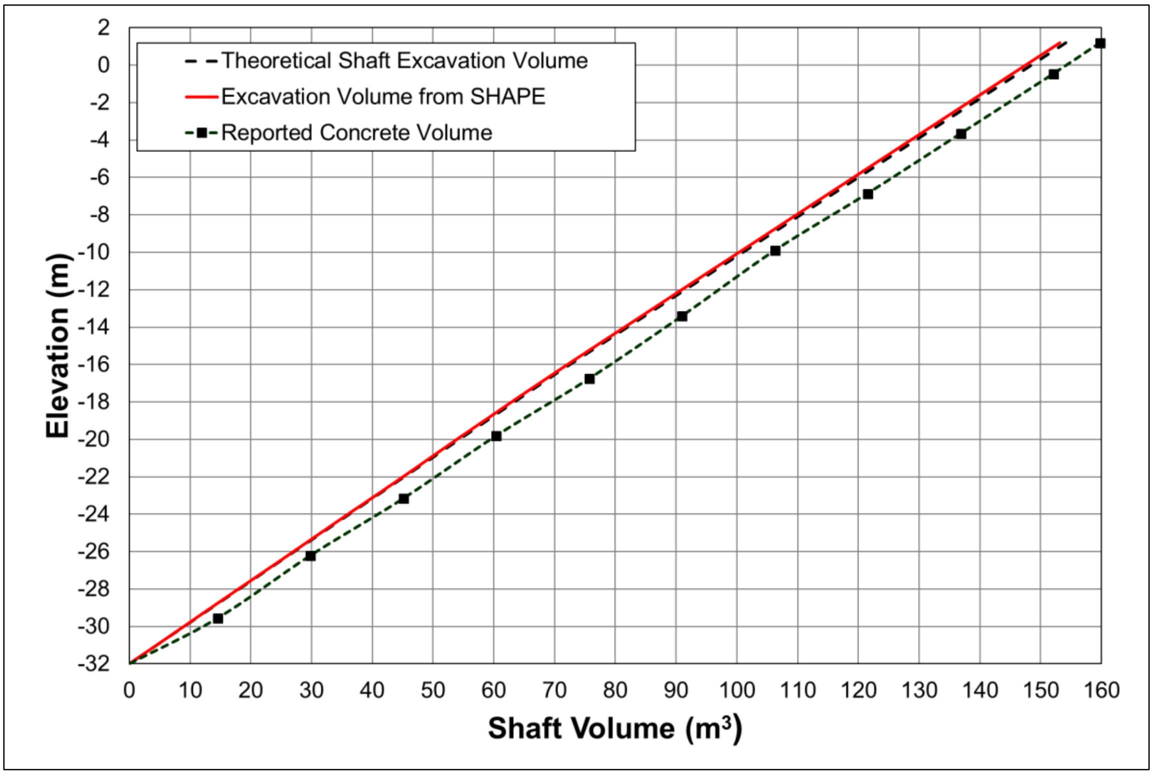


Figure 7. Comparison of Shaft Volumes Versus Elevation.

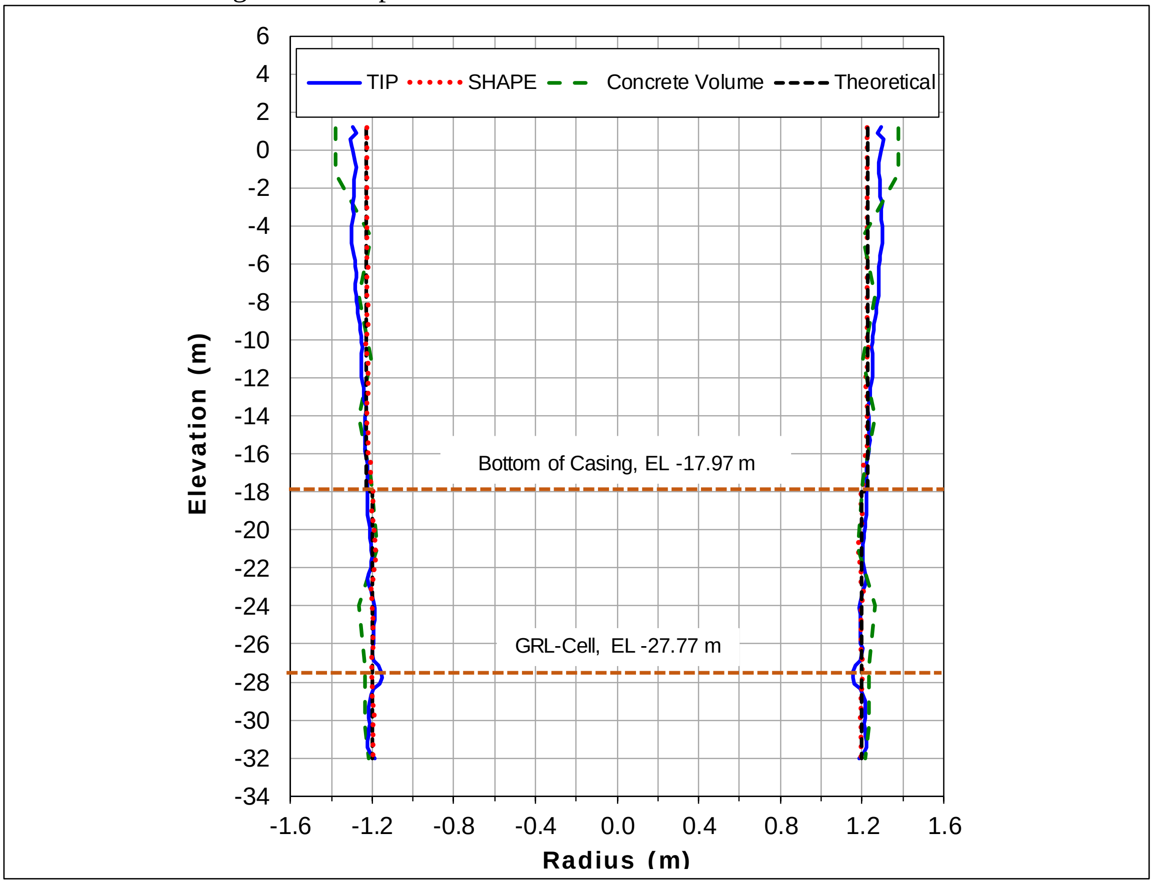


Figure 8. Comparison of Average Shaft Radius Versus Elevation.

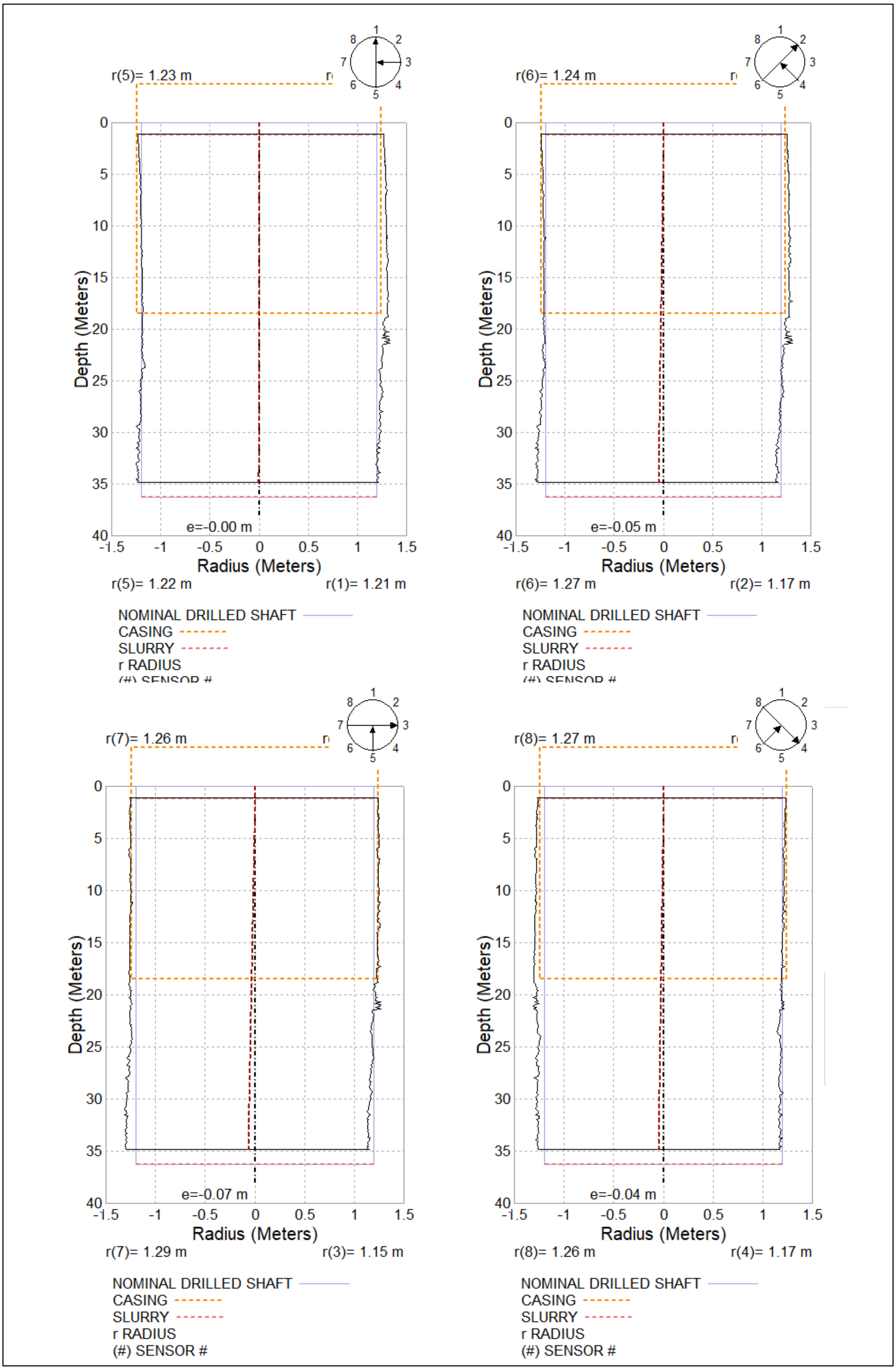
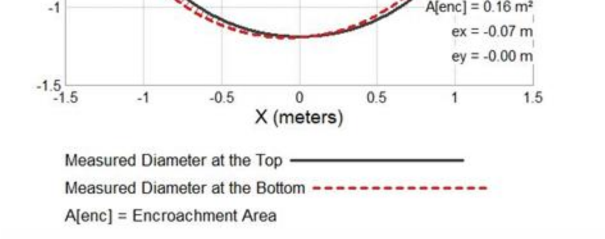

r(5)= 1.23 m
e=-0.00 m
Depth (Meters)
Radius (Meters)
r(5)= 1.22 m
r(1)= 1.21 m
NOMINAL DRILLED SHAFT
CASING
SLURRY
r RADIUS
r(6)= 1.24 m
e=-0.05 m
Depth (Meters)
Radius (Meters)
r(6)= 1.27 m
r(2)= 1.17 m
NOMINAL DRILLED SHAFT
CASING
SLURRY
r RADIUS
r(7)= 1.26 m
e=-0.07 m
Depth (Meters)
Radius (Meters)
r(7)= 1.29 m
r(3)= 1.15 m
NOMINAL DRILLED SHAFT
CASING
SLURRY
r RADIUS
(#) SENSOR #
r(8)= 1.27 m
e=-0.04 m
Depth (Meters)
Radius (Meters)
r(8)= 1.26 m
r(4)= 1.17 m
NOMINAL DRILLED SHAFT
CASING
SLURRY
r RADIUS
(#) SENSOR #

Figure 9. SHAPE Results of Shaft Radius Versus Depth.



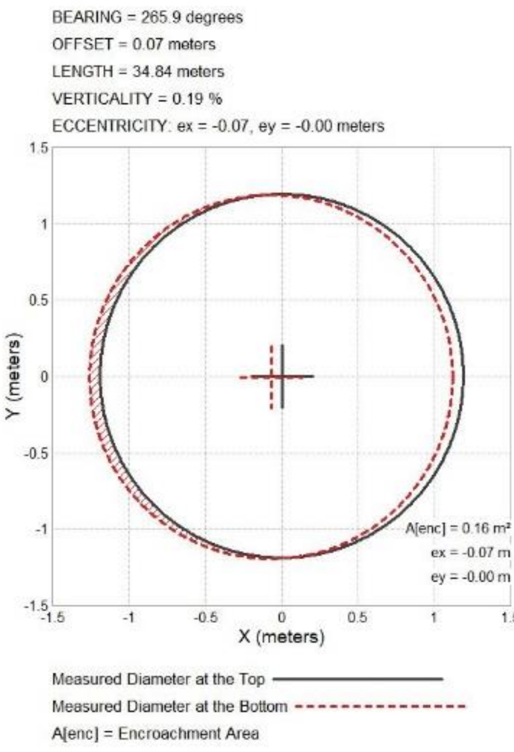
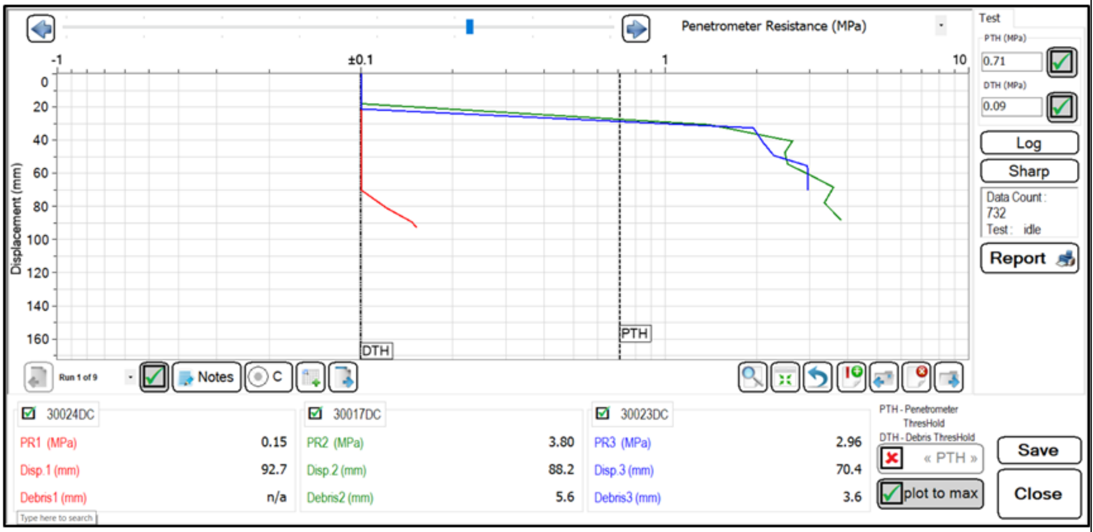


Figure 10. SHAPE Results of Shaft Radius Versus Depth.

Center



North

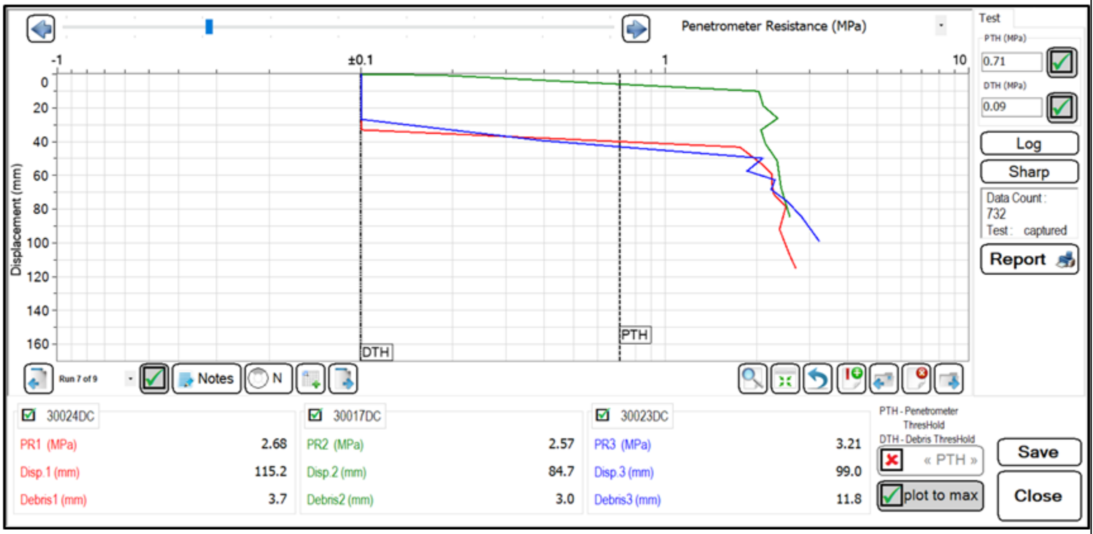
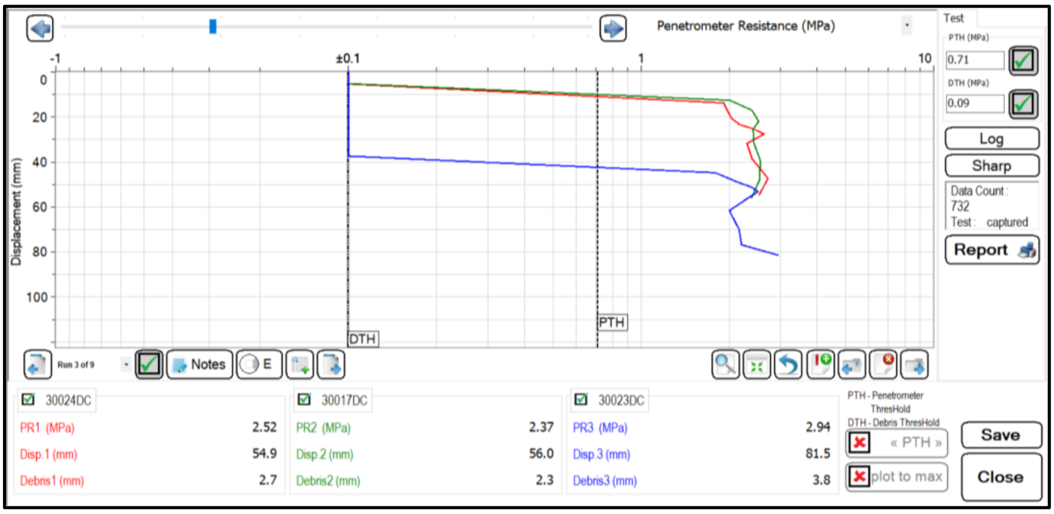


Figure 11. SQUID Results at Shaft Center and North Quadrant.

East



West

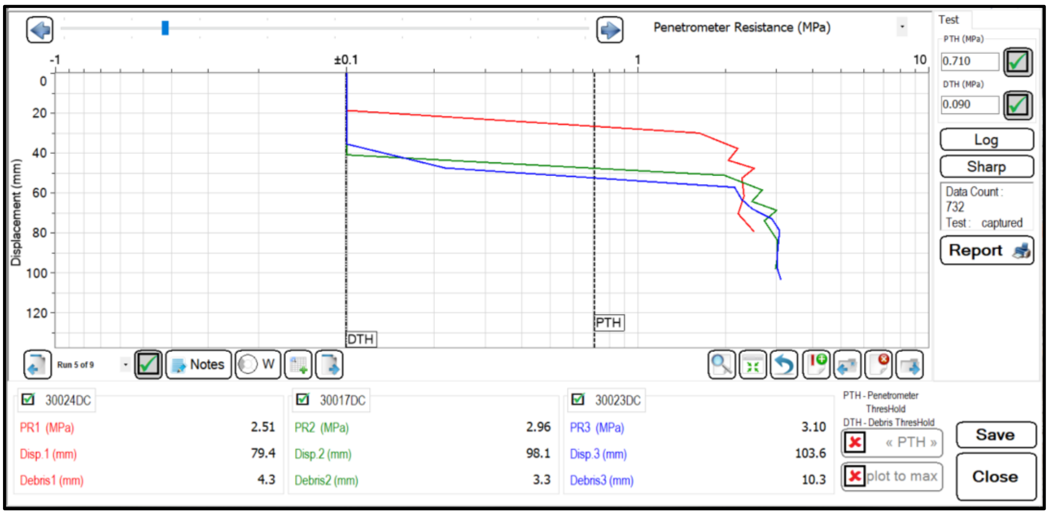


Figure 12. SQUID Results at East and West Quadrants.

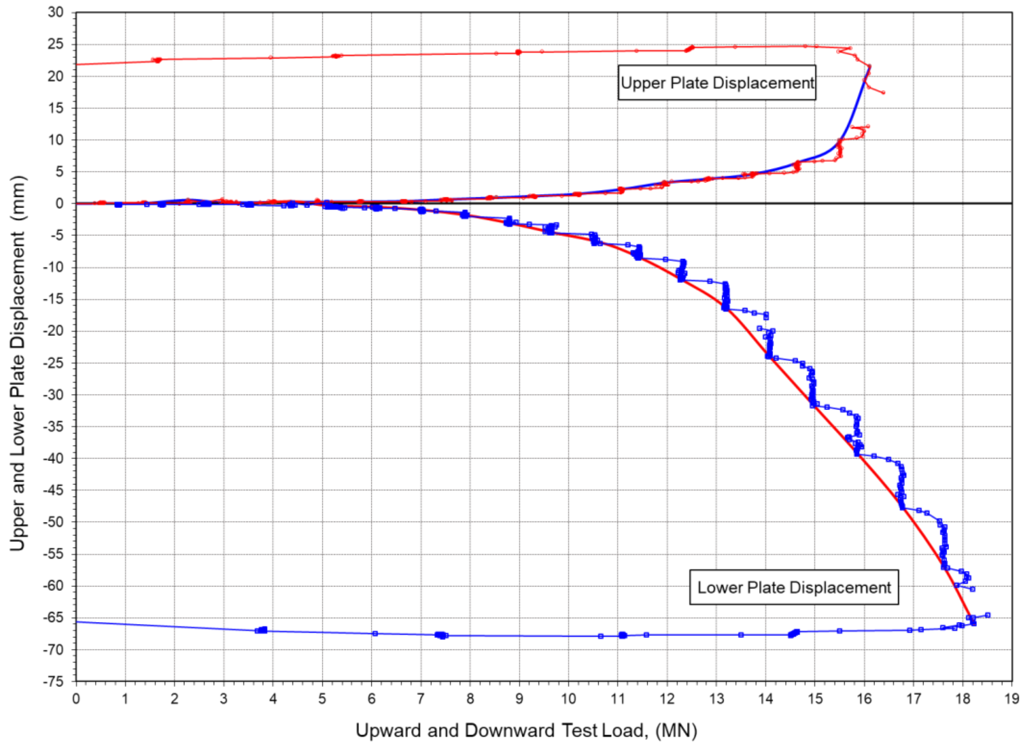


Figure 13. BDSLT Upper and Lower Bearing Plate Movement vs Jack Load.

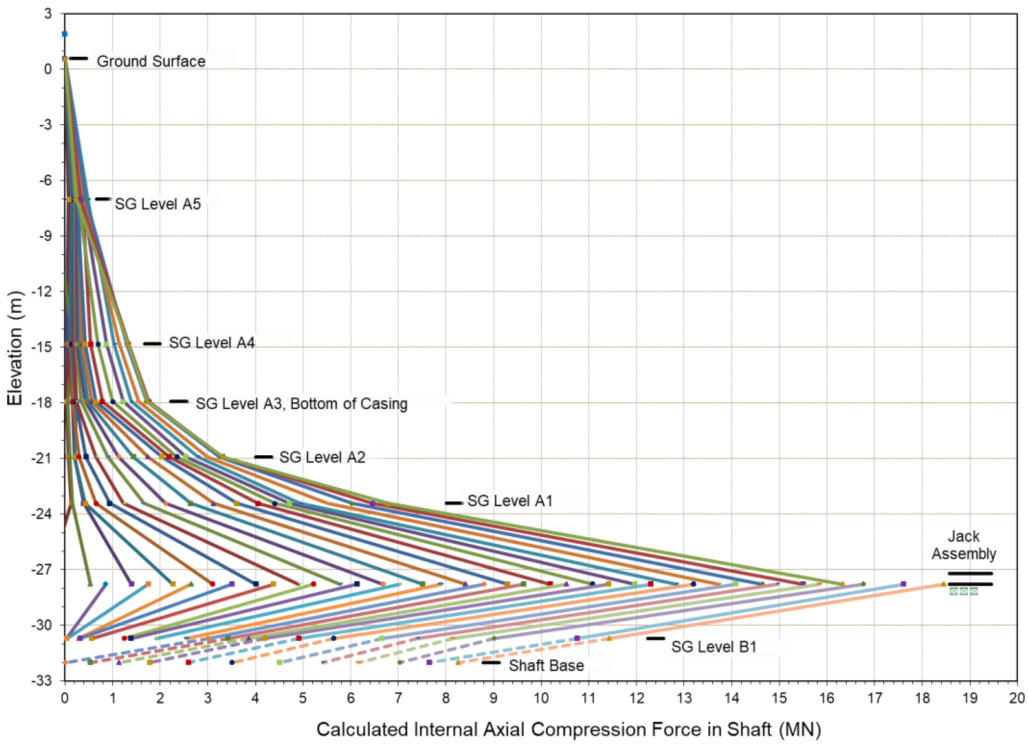


Figure 14. BDSLT Determined Internal Force Profile vs Elevation.

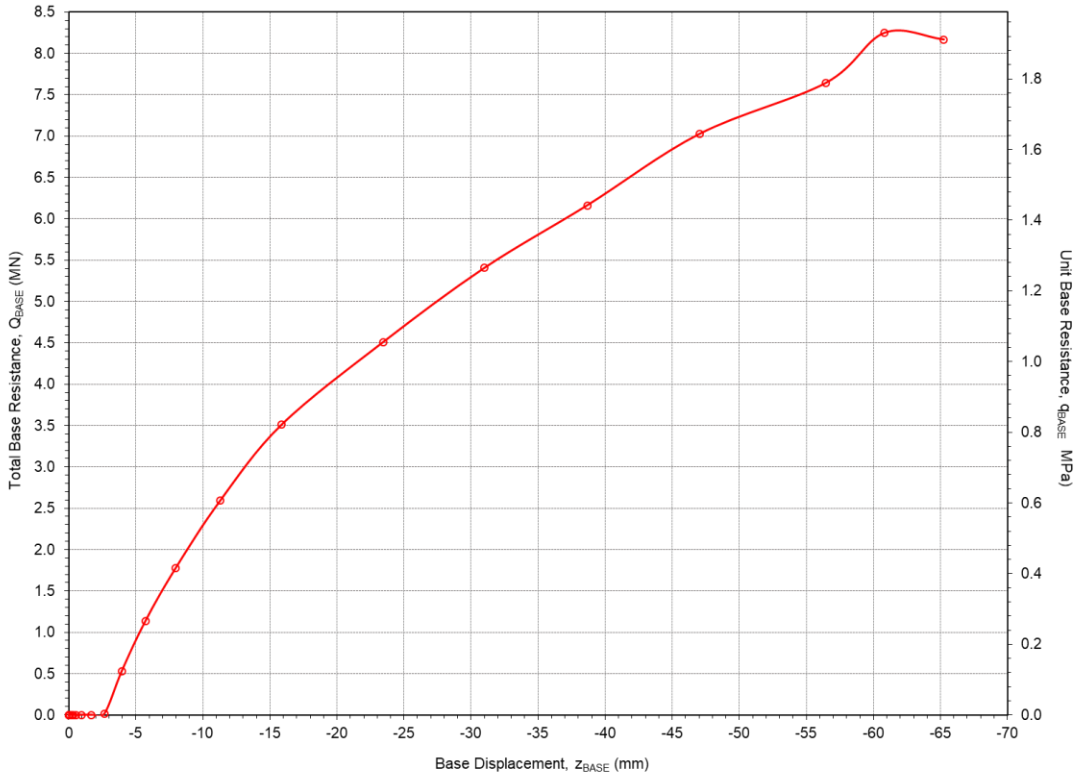


Figure 15. BDSLT Determined Total and Unit Base Resistance vs Base Displacement.

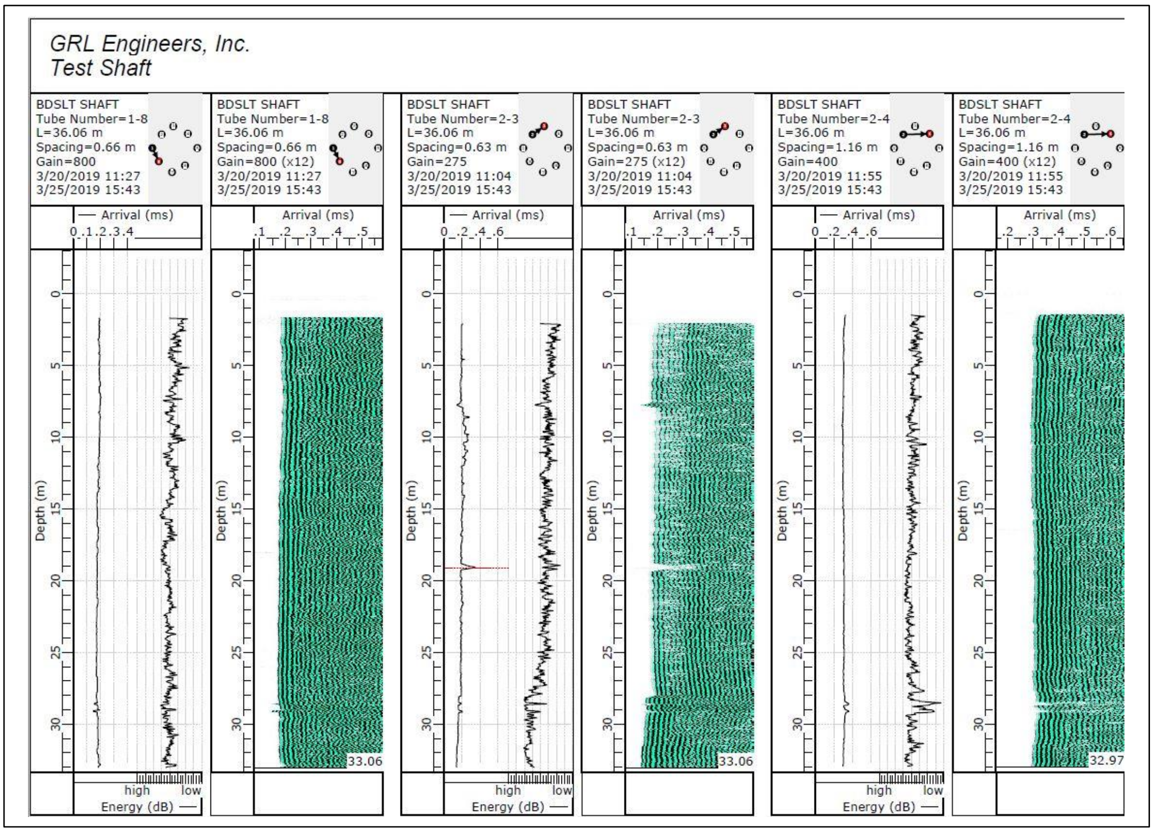


Figure 16. Representative CSL Profiles 1-8, 2-3, 2-4.

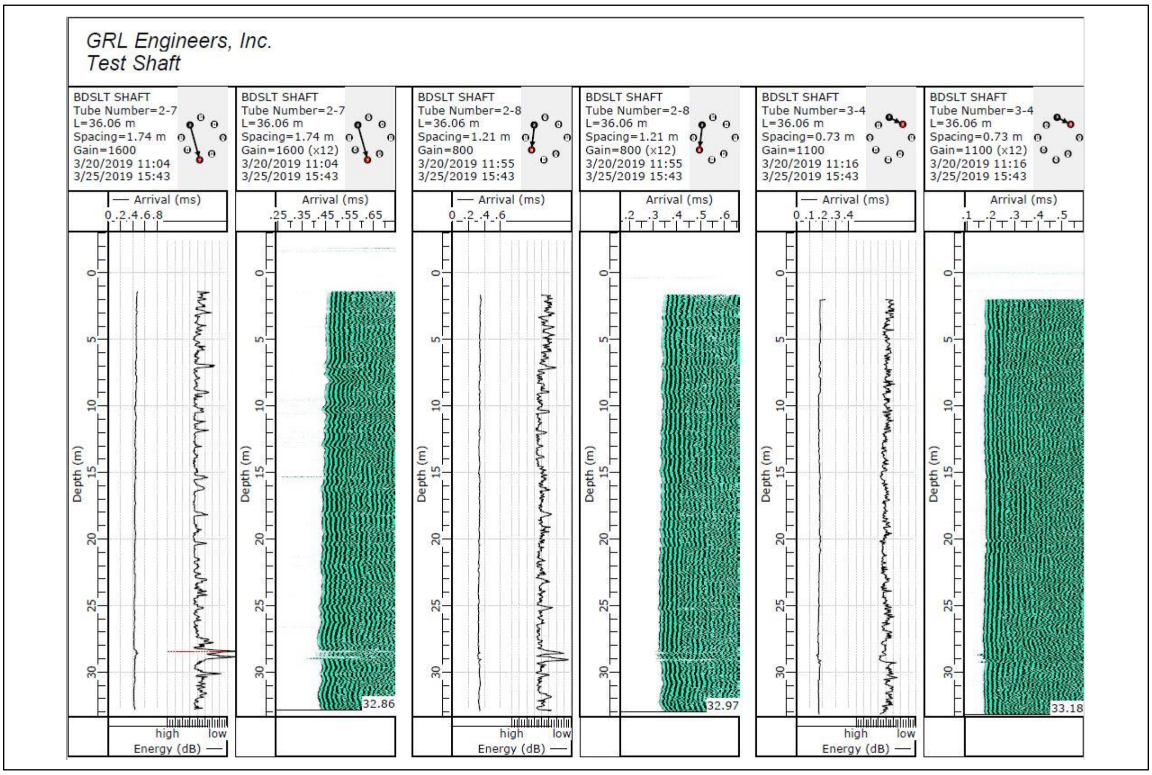
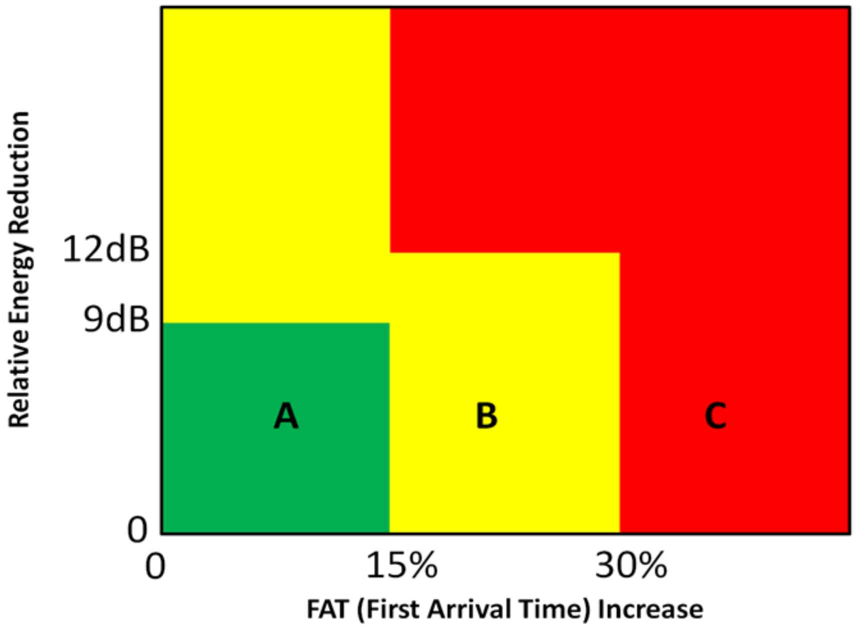


Figure 17. Representative CSL Profiles 2-7, 2-8, 3-4.



Class A: Acceptable CSL test results

- First Arrival Time (FAT) increases are less than 15% of the local average FAT value AND reductions in energy are less than 9 dB of the local average value of relative energy.

Class B: Conditionally Acceptable CSL test results

- First Arrival Time (FAT) increases between 15 and 30% of the local average FAT value AND reductions in energy are less than 12 dB of the local average value of relative energy.

or

- First Arrival Time (FAT) increases are less than 15% of the local average FAT value AND reductions in energy are greater than 9 dB of the local average value of relative energy.

Class B: Highly Abnormal CSL test results

- First Arrival Time (FAT) increases are greater than 30% of the local average FAT value.

or

- First Arrival Time (FAT) increases are greater than 15%% of the local average FAT value AND reductions in energy are greater than 12 dB of the local average value of relative energy.

Figure 18. Proposed CSL Rating Criteria (after DFI, 2019).

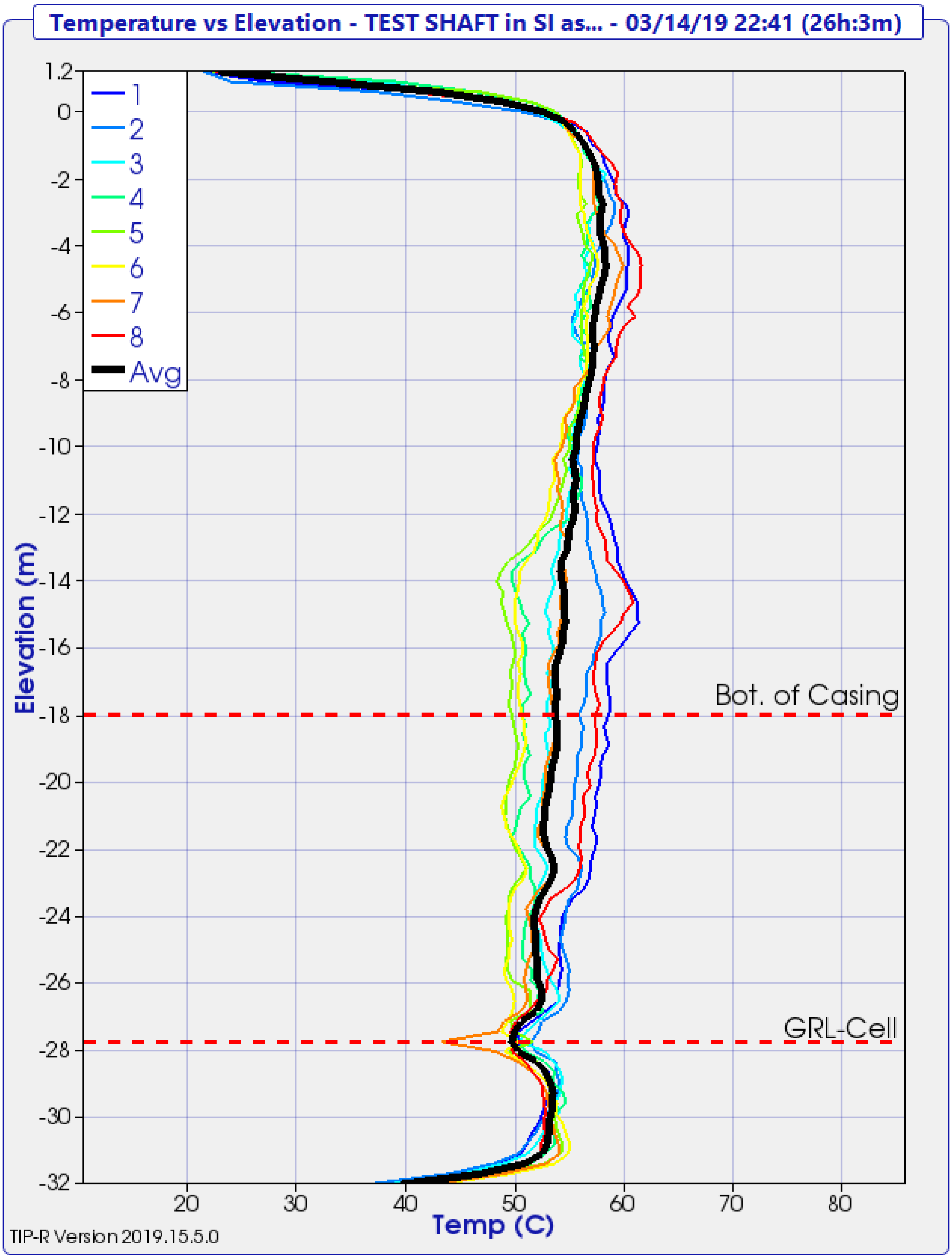


Figure 19. TIP Results: Temperature versus Elevation.

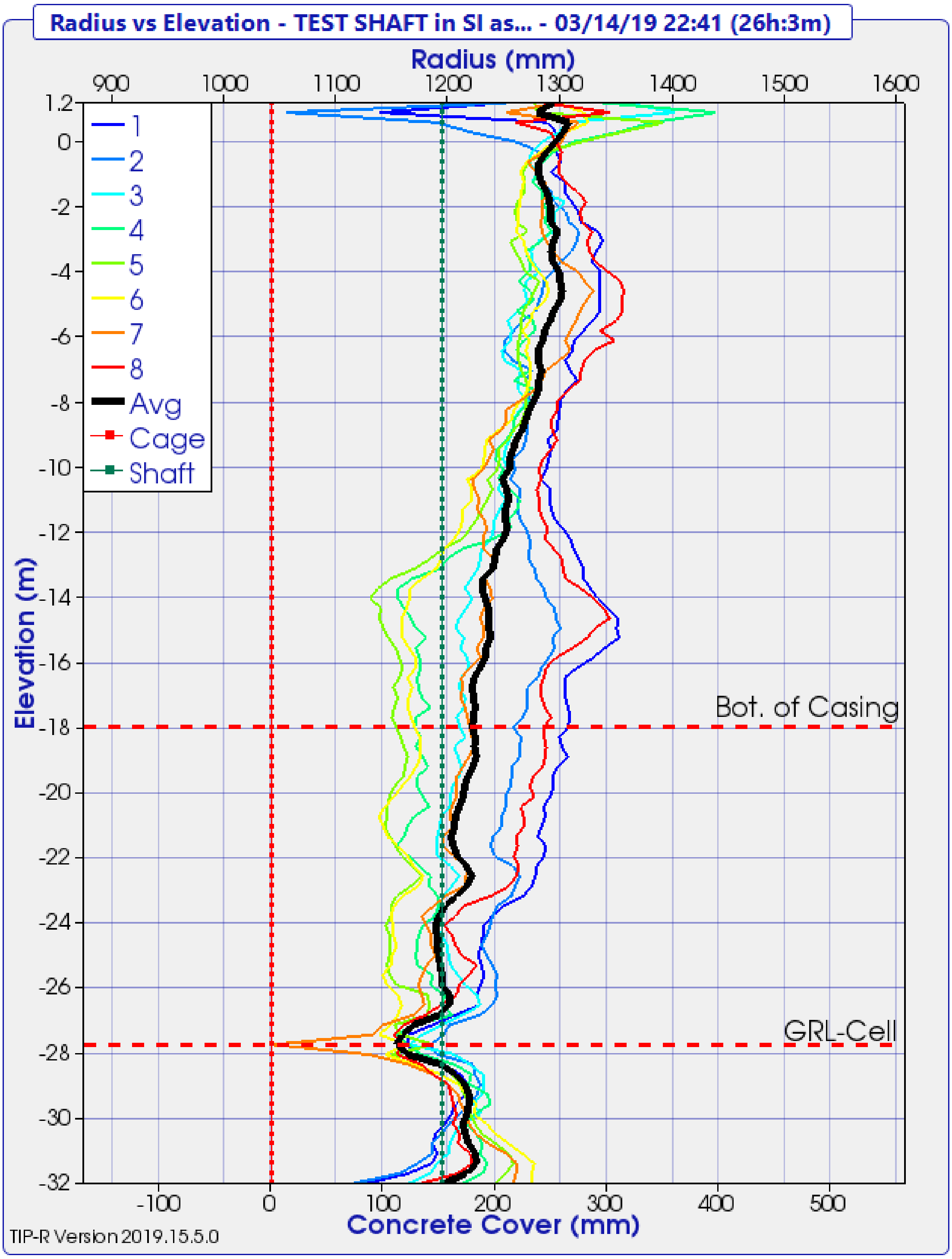


Figure 20. TIP Results: Radius and Concrete Cover versus Elevation.

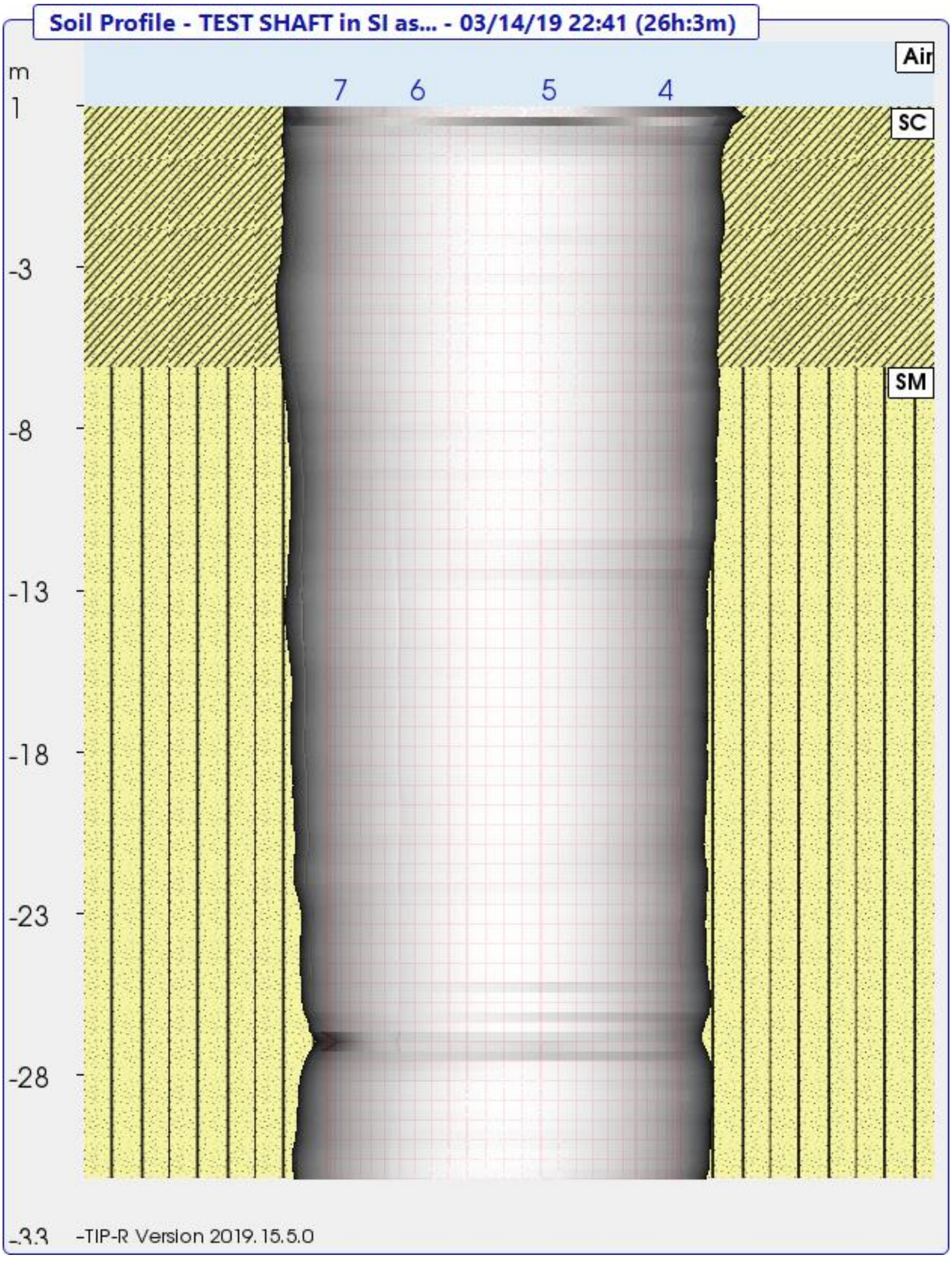


Figure 21. TIP Results: 3D Depiction with Reinforcing Cage Overlay Versus Elevation.