Advances in Drilled Shaft Testing Techniques

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ABSTRACT

Drilled shafts are commonly used deep foundation systems throughout the world. For these foundation units to serve their intended purpose, they must be capable of carrying their required load both structurally and geotechnically. As the use of drilled shafts has become more prominent, techniques to verify their structural integrity and geotechnical load carrying capabilities have continued to evolve. Several recently developed testing techniques to assess drilled shaft structural integrity include thermal integrity profiling (TIP), the shaft quantitative inspection device (SQUID), and the shaft area profile evaluator (SHAPE). Also, as the size and design capacities of drilled shafts increase, the costs for traditional static load tests to verify capacities also has increased. As such, alternative techniques for evaluating drilled shaft geotechnical resistance have been developed that include high-strain dynamic pile testing (HSDPT) and bi-directional static load testing (BDSLT). This paper provides an overview of each of the testing techniques described above and sample data is presented.

RÉSUMÉ

Les fondations sur puit sont des types de fondations profondes q qui sont utilisés communément dans le monde entier. Pour que ces types de fondation remplissent leur fonction prévue, ils doivent être capables de supporter les charges exiges structurellement et geotechniquement à la même fois. Au fur que l'utilisation des puits forés est devenue plus considérable, les techniques de vérification de leur intégrité structurelle et de leurs capacités de soutenir les charges géotechniques ont continué d'évoluer. Récemment, plusieurs techniques de tests ont été développée pour évaluer l'intégrité structurelle des fondations sur puit. Ces techniques contiennent : le profilage d'intégrité thermique sait comme « Thermal Integrity Profiling (TIP) », le dispositif d'inspection quantitative de le puits forés sait comme « Shaft Quantitative Inspection Device (SQUID) » et l'évaluateur de profil de la surface de le puits forés sait comme « Shaft Area Profile Evaluator (SHAPE) ». En addition, à mesure que la taille et les capacités de conception et la demande des fondations sur puit augmentent, les coûts pour les tester et vérifier leurs capacités ont aussi augmenté. Comme résultants, des techniques alternatives pour évaluer la résistance géotechnique des fondations sur puit ont été développées. Ces techniques contiennent: High-Strain Dynamic Pile Testing (HSDPT) and Bi-Directional Static Load Testing (BDSLT). Cet article donnera une vue générale sur chacune de techniques décrites ci-dessus et beaucoup des exemples de données ont été présentés et discutes.

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, and 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 thickness of this material has traditionally been evaluated by bouncing a weighted tape off the bottom of the shaft excavation and qualitatively assessing the base sediment thickness. 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 does not provide a quantitative value of base debris thickness or measurements of material strength.

2.3 Concrete Quality/Shaft Integrity

The quality and integrity of drilled shaft concrete is extremely important to satisfying the foundation performance requirements. Construction issues such as cracks, necking, bulging, honeycombing, soil inclusion and loss of concrete cover over the reinforcing cage, can significantly affect the performance of a drilled shaft. Historically, non-destructive test (NDT) methods to assess the condition of the concrete within the shafts include crosshole sonic logging (CSL), low strain integrity testing (PIT, Sonic Echo or Impulse Response), and gamma-gamma logging (GGL).

Each of these methods has advantages and limitations. The simplest method, PIT which requires no preplanning or material cast into the shaft, has the greatest limitations since it can only be used to identify major cross-sectional changes. Both CSL and GGL require access tubes to be cast into the shaft but also provide a better evaluation of concrete quality. However, CSL cannot be used to evaluate the area of the shaft outside of the reinforcing cage and GGL can evaluate only the concrete immediately surrounding the access tube. GGL also has the disadvantage of having to store and transport radioactive material. In addition, CSL and PIT require the concrete to be cured sufficiently for testing, typically three to seven days. Also, none of these methods can be used to evaluate reinforcing cage alignment.

2.4 Load Testing

On some drilled shaft projects, site-specific load testing is specified. The testing can be performed to assess the side shear and end bearing resistances of the drilled shaft to either verify or refine the design or to prove that the shaft can support a given load as constructed. Load testing on a project also allows for increased resistance factors to be used in the design which could result in a more economical design.

This testing has traditionally been performed as conventional top-down static load tests with a hydraulic jack and reaction system. However, as the size and design capacities of drilled shafts increase, the costs and time required to design, construct, perform, and evaluate conventional static load tests also has increased.

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 innovative and powerful 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 stem, 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.

Figure 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, 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 and this time, along with the associated wave speed, is used to calculate the distance to the sidewall. 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 laser technology to determine both the geometry and the distance from the 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 (Hannigan et al. 2021). 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 1,427 m/sec was determined. Sensors 5, 6, and 7 have the longest arrival times indicating that the distances from the center of the device to those excavation sidewalls are the longest. Conversely, sensors 2 and 3 have the fastest arrival time indicating that the distances from the center of the device to those excavation sidewalls are the shortest. On the right-hand side, an X-Y plot of the excavation radius from its starting centroid is displayed. The data indicate that the centroid of the excavation at this depth is east and slightly north from its starting coordinates.

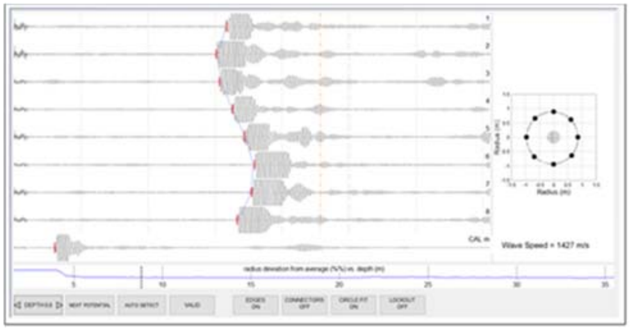


Figure 2. Ultrasonic signals at one test depth.

Figure 3 presents profiles of sensors 5-1, 6-2, 7-3, and 8-4, left to right, through a different drilled shaft excavation. Note that sensor 1 and sensor 5 are located on the north and south sides of the device, respectively.

In this example, the centroid of the base of the excavation is clearly northwest of the centroid of the top of the excavation. The calculated eccentricity in Profiles 5-1, 7-3, and 8-4 ranged from 0.18 m to 0.27 m. Figure 4 presents the maximum calculated eccentricity in the excavation and the resulting verticality of 2.91%.

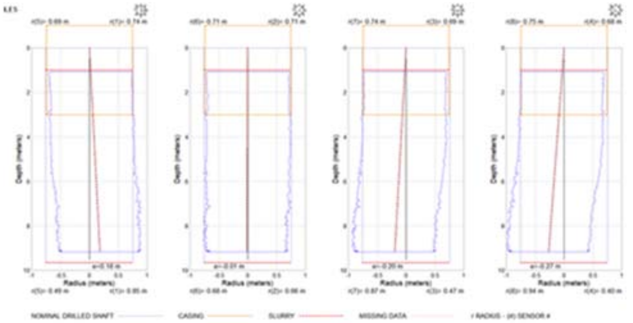


Figure 3. N-S (5-1), NE-SW (6-2), E-W (7-3), and SE-NW (8-4) profiles of radius vs depth through excavation

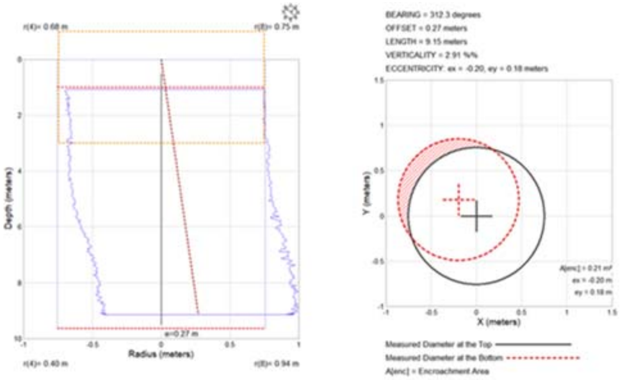


Figure 4. Maximum calculated eccentricity and resulting excavation verticality

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 force required to penetrate harder materials at the excavation base. After the device is pinned to the Kelly bar, the typical total time required to complete the standard base cleanliness evaluation tests at the shaft center and at the four orthogonal sides is 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 5, 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).

Figure 5. Shaft Quantitative Inspection Device

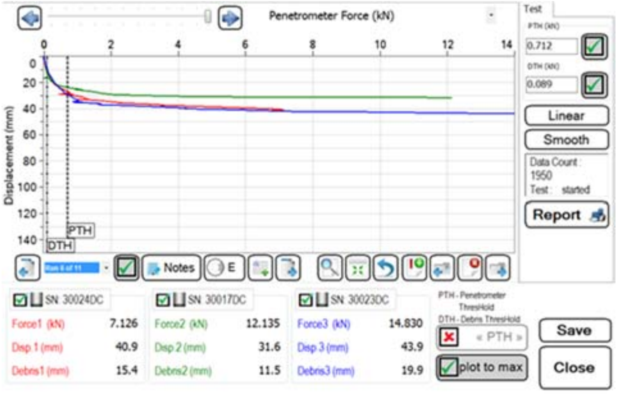
The analysis considers two penetration resistance thresholds, one associated with the penetration resistance defining debris, DTH, and the second defining the penetration resistance offered by natural material, PTH. Each penetration resistance threshold is marked with a vertical line in the output plots. 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 6a, 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 drilling fluid for four days prior to the testing. Due to degradation of the 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 6b, indicated from 11.5 mm to 19.9 mm of debris which was below the project specification limits.

PTH (kN) 0.712 ☑
DTH (kN) 0.089 ☑
Data Count : 143
Test : idle

☑ SN 30024DC		☑ SN 30017DC		☑ SN 30023DC	
Force1 (kN)	6.986	Force2 (kN)	9.093	Force3 (kN)	0.307
Disp 1 (mm)	141.6	Disp 2 (mm)	135.9	Disp 3 (mm)	158.5
Debris1 (mm)	126.2	Debris2 (mm)	123.5	Debris3 (mm)	>153.0

Figure 6a. SQUID results from shale bedrock exposed to drilling fluid for four days



PTH (kN) 0.712 ☑
DTH (kN) 0.089 ☑
Data Count : 1950
Test : started

☑ SN 30024DC		☑ SN 30017DC		☑ SN 30023DC	
Force1 (kN)	7.126	Force2 (kN)	12.135	Force3 (kN)	14.830
Disp 1 (mm)	40.9	Disp 2 (mm)	31.6	Disp 3 (mm)	43.9
Debris1 (mm)	15.4	Debris2 (mm)	11.5	Debris3 (mm)	19.9

Figure 6b. SQUID results from shale bedrock redrilled and cleaned by air lifting

3.4 Concrete Quality/Shaft Integrity - TIP

The most recent advance in drilled shaft integrity testing uses the hydration temperature of the shaft concrete to assess concrete integrity as well as reinforcing cage alignment, and concrete cover. The Thermal Integrity Profiling (TIP) method uses Thermal Wire$^{®}$ cables that are attached to the reinforcing cage prior to casting the shaft. The thermal wires have temperature sensors evenly spaced, typically every 305 mm, along the length of each wire. One thermal wire is installed for each 305 mm of drilled shaft diameter, rounded to the nearest whole number and evenly spaced around the reinforcing cage (Piscsalko et al. 2018).). Procedures for performing the test are further described in ASTM standard D7949.

After placing the reinforcing cage, and prior to or immediately after completion of the concrete pour, a Thermal Aggregator (TAG) is attached to one wire and as many Thermal Acquisition Ports (TAP-Edge) data logging units as necessary are attached to the remaining wires. The thermal wires begin collecting data immediately after they are connected to the logging units. The temperature of each thermal sensor is read by the data loggers, typically every 15 minutes, and the temperature readings are pushed to the Cloud server for real time analysis (Hannigan et al. 2021). By utilizing the Cloud server, data collection costs as well as data analysis and reporting time are reduced.

As the concrete cures, heat is generated by the hydrating cement which increases the temperature within the shaft. The measured temperature at each sensor location provides a profile of temperature versus depth at each time increment. These results can be evaluated for element shape and integrity, concrete quality, the relative location of the reinforcing cage, and concrete cover.

The overall average temperature of all Thermal Wire readings for a given foundation element over the embedded depth can be directly related to the overall volume of concrete installed. For drilled shafts, the integrity can, therefore, be assessed based on the average temperature measurements from each Thermal Wire at each depth increment. If the measured average temperature is consistent over the monitored range of depths, the shaft is considered to be of uniform shape and quality. Bulges can be identified as localized increases in average temperature, while insufficient concrete quality or section reductions can be identified as localized decreases in average temperature. Anomalies present over more than ten percent of the effective cross-sectional area are generally indicated in multiple Thermal Wire cables at the same depth. Because soil and slurry pockets produce no heat, areas of soil intrusion or inclusion are indicated by lower, local temperatures.

Reinforcing cage location can be estimated based on the relative temperature difference between an individual Thermal Wire cable and the average of all cables. Higher individual Thermal Wire temperatures indicate that the cable is closer to the center of the bored pile, or near a local bulge, while lower individual Thermal Wire temperatures indicate that the cable is closer to the soil-pile interface, or to a local defect. By viewing diametrically opposite Thermal Wire® cables, vertical zones where a lateral shift of the reinforcing cage has occurred can be determined if one cable temperature is higher than average and the diametrically opposite cable temperature is lower than average (Hannigan et al. 2021).

Figure 7 presents a photograph of the thermal wire cables extending above the top of a concreted shaft with the end of each cable attached to a data logger.

Figure 7. Thermal wire cables attached to data loggers

Figure 8 presents Thermal Integrity Profiling results for a 1524 mm diameter drilled shaft (Hannigan et al. 2021). The leftmost plot presents the measured temperatures versus depth. Note that the shaft has a relatively uniform temperature versus depth with the exception of the top and bottom as well as near a depth of 11.5 meters. The top and bottom temperature variations are normal where the shaft temperature rolls off to the air temperature at the top and the soil temperature at the base. These environmental influences can be modeled and test results adjusted for their effects as described by Piscsalko et al. (2016). In the center plot, the average temperature of all Thermal Wire readings over the embedded depths has been related to the overall volume of concrete installed to yield the pile radius versus depth and the concrete cover versus depth. The significant drop in temperature near 11.5 m indicates a severe integrity concern. The temperature of four wires is greater than a 6% reduction warranting further evaluation. Concrete core holes encountered a 150 mm thick void at this location necessitating shaft remediation. A 3D representation of the shaft and cage overlain on the soil description is presented in the rightmost plot.

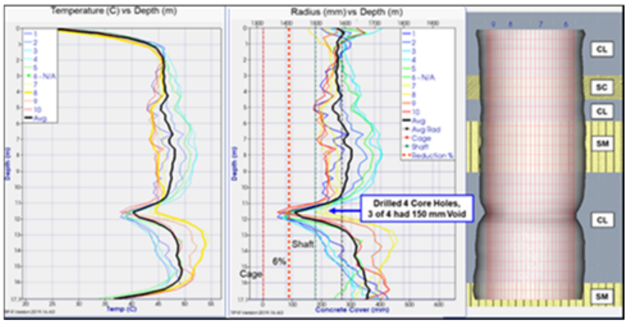


Figure 8. Thermal Integrity Profiling results from a drilled shaft

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

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

3.5 Load Testing – High-Strain Dynamic & Bi-Directional

3.5.1 High-Strain Dynamic Testing

High-strain dynamic pile testing (HSDPT) is a quick and less costly alternative to conventional static load testing using hydraulic jacks and reaction systems. The application of HSDPT was initially developed for driven piles but is also being applied to drilled shafts and other cast-in-situ elements.

A main difference between driven pile testing and drilled shaft testing is that the former is usually tested by using a pile driving hammer (diesel, hydraulic, air-steam etc.), whereas the latter is tested by means of a large drop weight with only a few, well controlled impacts for better stress and energy control. Typically, three to five impacts are applied for a successful dynamic load test on a drilled shaft. The impact load should be sufficient to generate an adequate permanent pile penetration to mobilize either the ultimate shaft capacity (test to failure) or a specified test load (proof test). The drop height and, therefore, the applied energy is increased from blow to blow until an adequate set (permanent displacement) for the mobilization of the capacity is reached, without stresses exceeding the allowable limits. Figure 9 shows a typical guide and drop weight system.

Figure 9. Drop weight system for drilled shaft testing

Dynamic load tests are performed in general accordance with ASTM D4945. To perform the test, the applied force from the weight impacting the drilled shaft is measured from a shaft top force transducer. In a similar manner, the shaft top velocity is evaluated from accelerometers bolted to the side of the shaft. Data from the instrumentation are conditioned, digitized, stored and processed with a Pile Driving Analyzer® (PDA) system. A drilled shaft, instrumented for dynamic testing is shown in Figure 10.

The dynamic measurements of strain and acceleration are subjected to a rigorous analysis to calculate static pile capacity using CAPWAP (CAse Pile Wave Analysis Program) software. The CAPWAP method is a signal matching process (or reverse analysis procedure), in which the measured input and an assumed soil model are used to obtain a calculated response that matches the measured input. Soil model parameters are adjusted until good agreement between measured and calculated signals is obtained. CAPWAP is used for both uniform and non-uniform piles/shafts.

Figure 10. Instrumented drilled shaft for HSDPT

The completed CAPWAP analysis yields the mobilized total bearing capacity, shaft resistance distribution, end bearing, soil damping and stiffness parameters and a simulated static load-displacement curve. The load-displacement graph is based on the CAPWAP calculated static resistance parameters and the elastic compression characteristics of the shaft. Figure 11 provides CAPWAP analysis results for a 1220-mm diameter drilled shaft, approximately 18.5 m long.

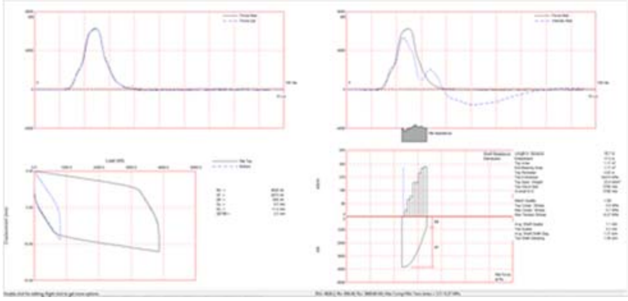


Figure 11. CAPWAP results for 1220-mm drilled shaft

3.5.2 Bi-Directional Static Load Testing

As the size and design capacities of drilled shafts continue to increase, the costs and time required to construct and complete conventional top-loading static load tests also increase. Bi-directional static load testing (BDSLT) is a recently developed method of testing that can be advantageous for determining mobilized side-shear and end-bearing resistances at lower cost compared to conventional top-loading static load tests.

BDSLT incorporates a hydraulic jack embedded within the foundation element (Figure 12), commonly at a selected depth intended to result in equal resistance above and below the jack assembly, therefore targeting maximized total measured resistance (Robertson et al. 2020). As the jack is pressurized, it loads the foundation element in two directions, pushing upward against the shaft resistance of the portion of the foundation element above the jack location and, at the same time, downward against the shaft resistance below the jack and against the shaft base resistance. Once geotechnical failure occurs in either direction, the test is complete.

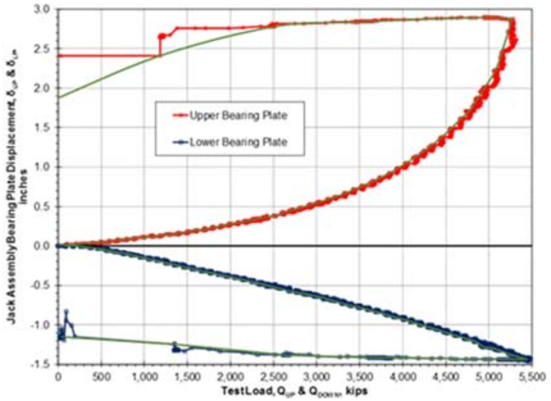
Figure 12. Jack assembly, showing upper and lower bearing plates

Embedded instrumentation such as displacement transducers and strain gages are typically used to evaluate displacements, elastic compressions, internal forces, as well as mobilized side-shear, end-bearing, and total resistances.

Results from a BDSLT typically include a plot of the upper and lower jack assembly bearing plate displacements as a function of test load as shown in Figure 13 (Komurka et al. 2019). A review of this figure indicates that the test was limited by geotechnical failure of the foundation portion above the jack assembly at an approximate upward test load of 5,270 kips (23,440 kN). As such, shaft resistance was likely fully (or nearly fully) mobilized above the jack assembly and likely not fully mobilized below the jack assembly.

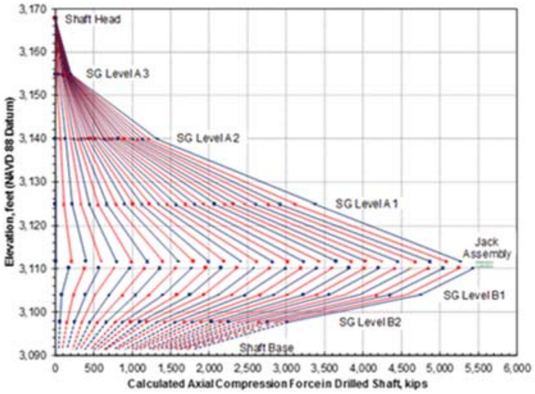
Internal forces within the shaft can be calculated at each strain gage level by converting average measured strains to forces. From these forces, unit shaft and base resistances can be evaluated. Figure 14 presents calculated internal force profiles for varying load increments from the same BDSLT.

Based on the relationship between shaft displacement and shaft resistance, both above and below the jack, equivalent top-loading (ETL) load-displacement curves can be generated. Figure 15 presents these curves for the previously referenced BDSLT and includes curves for shaft, base, and total load-displacement relationships.



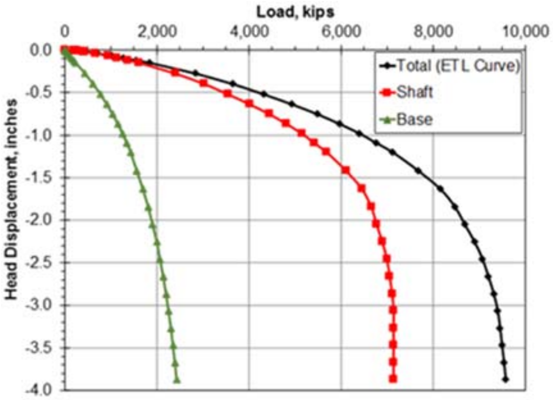
1 inch = 25.4 mm; 1 kip = 4.448 kN

Figure 13. Jack assembly upper and lower bearing plate displacement



1 foot = 0.3048 m; 1 kip = 4.448 kN

Figure 14. Calculated Axial Internal Compression Force Profiles



1 inch = 25.4 mm; 1 kip = 4.448 kN

Figure 15. Equivalent Top-Loading Curve

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 structural integrity and geotechnical load carrying capabilities have continued to evolve. This paper has provided an overview of several recently developed or evolved technologies that can be used for drilled shaft construction to provide timely and cost-effective quality control and quality assurance.

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