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DEEP FOUNDATIONS

SPECIAL ISSUE: QUALITY ASSURANCE & VERIFICATION

Rapid Load Testing in Barcelona

Embedded Data Collectors

QA Tools for Drilled Shafts

Anomalies, Flaws and Defects

Retire the SPT?

Test shaft construction in San Diego, Calif.

QUALITY ASSURANCE & VERIFICATION SPECIAL ISSUE:

FEATURE ARTICLE

Drilled Shaft Quality Assurance Tools: Interpretation and Impact

Quality assurance (QA) in drilled shaft foundations typically relies on observations and measurements taken from the ground surface. However, as technology has advanced, sensors lowered into access tubes or instrumentation embedded within the drilled shaft have become more common. An overview of many quality assurance and quality control (QA/QC) methods available to the industry are discussed in "A Comparison of Quality Management for Bored Pile/Drilled Shaft Foundation Construction and the Implementation of Recent Technologies," which was published in the *DFI Journal* (Hertlein, Verbeek, Fassett, and Arnold; 2016, v.10, n.2). In addition, full-scale load testing has become more common and accessible on most projects.

While the technology exists to obtain many types of data from sensors and instrumentation, the interpretation of the measured data is not always straightforward. Erroneous interpretation can be worse than no information. Categorization, which is frequently arbitrary, and numerical thresholds attempt to provide objectivity and uniformity to those that interpret the data. However, those acquiring the data or on-site "decision-makers" are often not part of the engineering design team. It should be the responsibility of the design team to evaluate all construction observations and collected data in conjunction with the design requirements. This is particularly important to assure that unnecessary, expensive and time-consuming replacement or remediation procedures are not hastily required and performed.

Experience suggests that decisions to remediate, or even reject a foundation, tend to be weighted disproportionally to anomalies identified with sensor and instrumentation data rather than to direct construction observations. In addition, decision-makers are often ill-equipped to properly evaluate the data or fail to analyze the data integrated with all direct observations and design criteria. A panel was assembled at the DFI 43rd Annual Conference on Deep Foundations in October 2018 to discuss this issue. A paper, authored by this panel and titled "Terminology and Evaluation Criteria of

Heavily instrumented rebar cages in San Diego

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Crosshole Sonic Logging (CSL) as Applied to Deep Foundations," should be available this year through DFI.

Ultimately, deep foundations are used to limit the displacement of the structures they support to a tolerable level. The engineer-of-record should be mindful of this when evaluating test results and should consider the impact any identified deficiencies or anomalies will realistically have on the actual performance of the foundation element. Instrumented load tests are invaluable tools to evaluate not only capacity but also constructability, quality and integrity. Load tests often show that less-than-perfect foundations will meet performance requirements. When the rejection of a drilled shaft occurs because of the QA data, implying the shaft will not accomplish its primary function, the authors argue that a direct measurement of that function, namely a load test, is highly beneficial.

Several examples of drilled shaft QA methods and how observation or load testing can feed back into a proper analysis are presented below.

Sidewall QA

Currently, there are no commonly used in-situ methods to assess filter cake or sidewall integrity of a drilled shaft excavation. Therefore, assessing the quality of the bond between the excavation sidewall and placed concrete requires constructing a shaft and performing a load test. If numerous load tests are performed on a given site, in similar geotechnical conditions, variations in the capacity results may be due to variations in slurry or tooling. However, quantifying the condition of the excavation sidewall is a topic where additional research and technology is needed. At times, it is clear from field observations and drilled shaft installation logs that a given shaft may not perform as expected and load testing tends to support such correlations. Direct measurement of sidewall integrity and filter cake during construction would vastly improve the correlation between quality of the sidewall-concrete bond.

Verticality and roughness can be assessed, with varying degrees of effectiveness, using commercially available mechanical or ultrasonic calipers. Verticality requirements mandated in standards and specifications often do not account for shaft diameter, encroachment or other factors that affect the structural performance of an out-of-plumb foundation element. While it is certainly important to enforce a maximum allowable deviation from vertical, a rational justification should be made when forcing a contractor to re-drill a shaft for no practical benefit.

ASTM D8232 (2018), *Standard Test Procedures for Measuring the Inclination of Deep Foundations*, was recently adopted to address the technology and its uses but further work is warranted. First, almost no specifications have referenced it because the standard is so new. Second, the International Building Code (IBC) and many local codes may supersede the ASTM standards, even if the ASTM standards are known. Local codes are often the most rigorous and inflexible. Decision-makers with knowledge are often powerless to make a proper value decision. Further discussion on this topic can be found in the *Assessment of Bored Pile Verticality Using an Ultrasonic Caliper* by Sinnreich et al published in the proceedings from the 2018 International Foundation Congress and Equipment Expo (IFCEE).

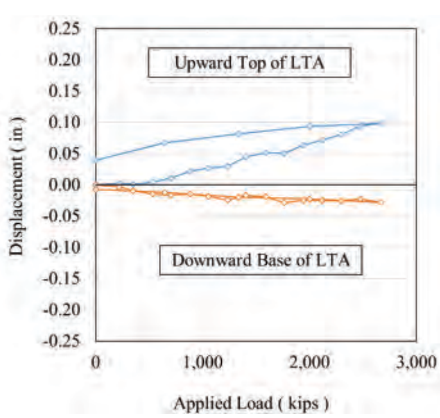
Shaft inspection devices (SIDs) can aid engineers as they try to verify tip conditions.

Slurry can affect side walls in unmeasurable ways and is impossible to see through.

Shaft Base QA

Historically, the bases of dry shaft excavations were evaluated by lowering an inspector down the hole. While uncommon today, when downhole inspection is performed, the excavation must be fully cased and dry. Experience suggests that full-length casings and dewatering schemes can drastically reduce the unit side resistance of a drilled shaft. Therefore, if downhole inspection is required, the engineer often must reduce or neglect skin friction. Ironically, this well-intended downhole QA procedure could actually result in a more expensive shaft, by disregarding potential side resistance and designing exclusively for end bearing. Although seeing and touching the shaft base may seem effective, it is still subjective. If there isn't feedback from load testing and creation of a database, the observational method doesn't provide value for future construction.

LoadTest Consulting (LTC) conducted a bi-directional load test on a recent project in Atlanta, Ga. The 6 ft (1.8 m) diameter shaft was socketed approximately 20 ft (6.1 m) into what is locally characterized as partially weathered rock (PWR). The test resulted in a unit end bearing resistance of 330 ksf (15.8 MPa), which was significantly higher than design expectations. A rock socket unit side resistance of 4.5 ksf (215 kPa) and an average overburden unit side resistance of 1.7 ksf (81 kPa) were measured. The total side resistance for the entire shaft was in excess of 2,600 kips (11.6 MN) at less than 1/10 in (2.5 mm) of displacement. Although designed for end bearing, the service load would have been supported in side resistance, and it was unlikely the load would ever make it to the shaft base.



Load-displacement relationship for bi-directional test in Atlanta, Ga.

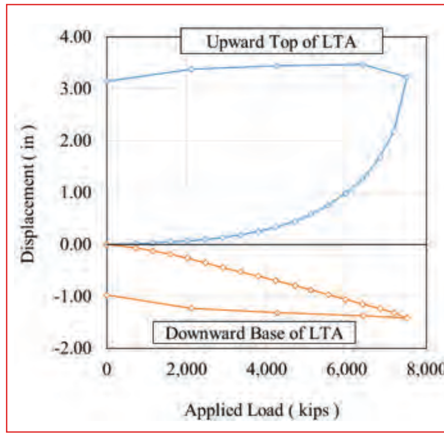
In many cases, wet excavations are still evaluated with a simple weighted tape. However, other sensor-based methods exist for QA assessment of the shaft base that do not require downhole entry. The most common are penetrometer systems, such as SQUID and Mini-SID type devices. Although these methods have the obvious advantage of keeping personnel out of deep excavations, they too introduce difficulties related to needed preparations (e.g., set up, materials, etc.) and interpretation.

On a recent project in San Diego, Calif., evaluation of the cleanliness of the bottom of the test shaft using a Mini-SID was specified. The excavation was accomplished using a spherical grab. The results of the Mini-SID indicated some sediment remained in the bottom of the shaft. However, in our experience, few or no uniform numerical criteria or standards exist to assess this type of excavated shape.

The shaft was load tested by LTC using the bi-directional test method. The load test measured a higher-than-expected end bearing resistance, with no indications of soft toe in the load-displacement curve.

San Diego project trestle bridge work area

With advancements in shaft bottom test methods and load testing performed on shafts that have employed these technologies, project specifications should be re-evaluated and adjusted with respect to acceptable bottom cleanliness criteria. Specifications should present a method for evaluating bottom cleanliness but should also include rational procedures if the criteria are not achieved. If end bearing is not a design component, expending considerable time testing and evaluating bottom cleanliness need not be specified. In addition, rejecting a shaft solely on a bottom cleanliness measurement, without considering all the observational data and design requirements, can lead to poor decisions resulting in large expense, delays, etc.



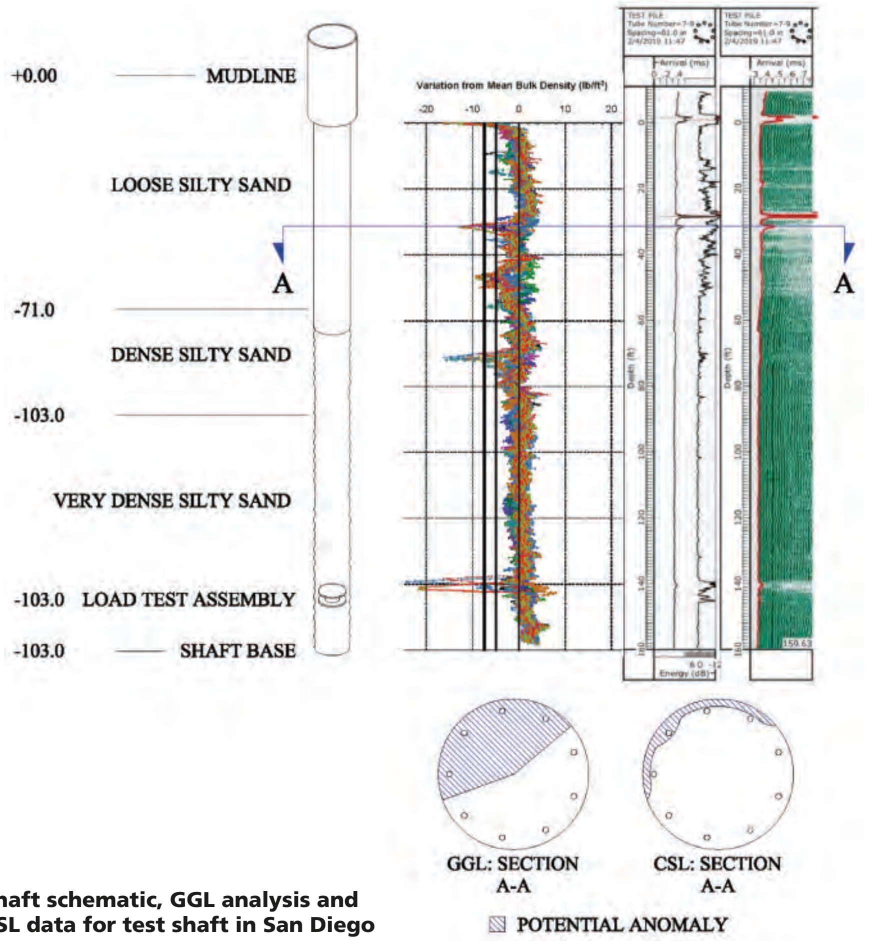
Load-displacement relationship for bi-directional test in San Diego

Use and Interpretation of QA Data

Typical drilled shaft integrity test methods include cross-hole sonic logging (CSL), gamma-gamma logging, (GGL), thermal integrity profiling (TIP) and low-strain dynamic testing (PIT). The chosen method is typically one favored by the engineer or contractor or based on local practice.

Frequently, if the favored method produces an undesirable result, the first instinct is to reject the shaft and call for a remediation plan. Remediation measures may include coring and grout injection or a complete replacement. Fortunately, a secondary method can often be used for additional evaluation, which may confirm or refute the original results.

On the same project in San Diego mentioned above, the test shaft included nine 2 in. (51 mm) PVC access pipes for GGL. The GGL results indicated several zones of



Shaft schematic, GGL analysis and CSL data for test shaft in San Diego

decreased bulk density, the most significant located near the elevation of the bi-directional jacks. Based on the GGL results, remediation of the shaft was proposed by the engineer prior to the planned bi-directional load test. Since remediation may have damaged the testing apparatus, rejection of the shaft was also proposed.

The owner and engineer subsequently decided to use the GGL access tubes for CSL testing of the shaft. Once the CSL waterfall plots were scaled and aligned to the correct elevations, it became apparent that the largest deviation from mean density in the GGL data was at the exact depth of the bi-directional jack assembly, which is a very heterogeneous zone composed of hydraulic jacks, instruments and cables along with concrete and rebar. Fortunately, the CSL results suggested only minor anomalies throughout the shaft.

LTC advised the owner to let the test proceed with the shaft "as is," due to the limited risk and high probability that useful integrity and performance information would be obtained. As mentioned previously, the load testing did not indicate any discernable detriment to performance from the anomalous zones as well as higher than expected skin and end bearing resistances. The strain gage data and compression data also indicated that the shaft's elastic behavior was very close to theoretical at the applied loads, indicating no structural defects in the concrete.

The authors are aware of numerous other examples of differing or contradictory shaft integrity results. While one technology is not superior to the other (e.g., CSL vs. GGL), using a second method can lead to either confirmatory or contradictory results. Contradictory results may be due to limitations in the technology or poor interpretation rather than actually missing a defect. However, two methods together provide significantly enhanced analytical value.

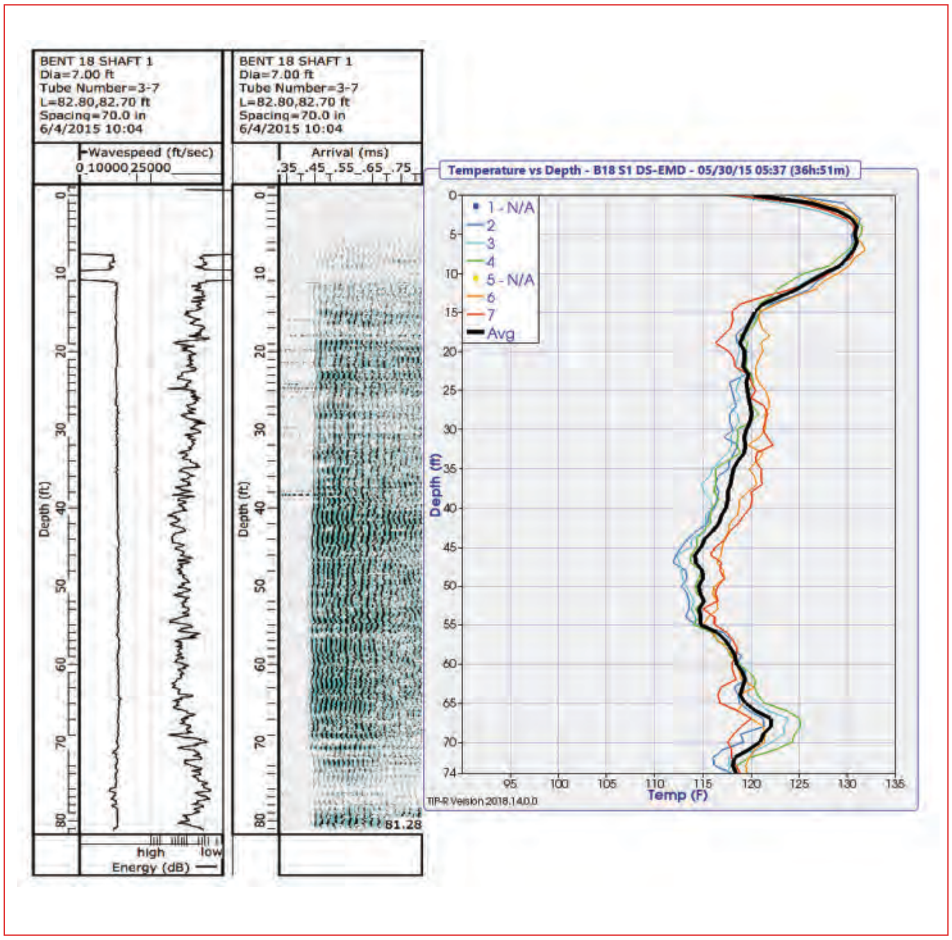
For years, GGL data in California suggested that end bearing in wet shafts was unreliable due to poor results near the shaft base. That is, the results from GGL testing indicated poor quality concrete; therefore, load transfer into end bearing was questioned and decreased unit end bearing resistance was used. Load tests performed on shafts with poor GGL results at the toe of the shaft did not indicate a soft toe but indicated relatively high unit end bearing resistance. In the authors' experience, the end bearing of shafts constructed under natural water or slurry are more likely to perform as expected, by an order of magnitude, compared to dry shafts based on actual full-scale load testing. Furthermore, of the hundreds of load tests of which the authors are aware where CSL, GGL or TIP results implied shaft integrity issues, only a

Shaft instrumented with TIP wires for a SCDOT project

handful yielded load test data that suggested any observable impact to the overall performance of the drilled shaft performance. Valuable shaft capacity may be neglected because of misinterpretation of QA data.

S&ME has been performing CSL on drilled shaft for South Carolina Department of Transportation (SCDOT) for nearly 20 years. Design requirements mandate that permanent construction casing be used and bleed water, which can be significant on large diameter shafts, must flow up alongside vertical reinforcing bars or CSL tubes because casing doesn't allow for horizontal flow. Experience suggests that bleed water relics attenuate the CSL signal, causing signal loss in the upper, cased portion of shafts.

While alarming at first, observations from coring have shown that the strength and integrity of shafts have not been compromised by the bleed water relics. This could be a case where QA results led to the rejection of a shaft if experience and observations during construction were not considered along with the test results. While signal loss is now understood, it does potentially mask true flaws that could exist. The TIP method, which isn't affected by bleed water, has been used by SCDOT as a companion test to CSL.



CSL and TIP test results for SCDOT project

Conclusion

Drilled shaft QA includes an impressive array of tools, but they often produce data that is open to ambiguous or even contradictory interpretation. Delays, additional expenses and even legal action can stem from the results of a single QA test. Quality evaluation should certainly be performed to give assurance of specific construction processes, but the foundation design and construction should be understood as a whole. Why, for example, evaluate bottom cleanliness at the expense of side resistance when end bearing is only a small fraction of total capacity?

Project specifications should consider advances in technology, and acceptance criteria should be reasonable and clearly stated. Specifications should not allow rejection of a foundation to depend on a single test method but rather encourage additional evaluation with other tools, if practicable. The engineer should consider construction observations and design criteria along with QA data when evaluating the acceptance or rejection of a deep foundation and should appreciate the significant impact on the schedule and overall project success. Load testing of foundations with instrumentation are invaluable tools to evaluate constructability, quality, integrity and performance, and often illustrate that foundations constructed under less than ideal conditions still meet (or exceed) performance criteria.

The authors suggest that more time should be spent evaluating side wall conditions, where significant side resistance may be available. The industry would benefit from the development of better testing methods specific to the shaft side wall and quantify how tooling and drilling fluid effect side resistance.

Ironically, contractors are often reluctant to spend any more than the minimum on QA or testing, seeing it as an expense or potential liability rather than an economic benefit. The contractor should embrace QA but should also insist it is fair and properly used. Significant work must be done to align technology with knowledge and economics.

Jon Sinnreich and Robert Simpson are co-founders and principals at LTC. Each has over 20 years of experience with bi-directional load testing and ancillary deep foundation testing. Greg Canivan is a technical principal at S&ME with over 20 years of experience in nondestructive and load testing. He manages S&ME's deep foundation testing group. In addition to their participation in DFI's Testing and Evaluation Committee and other DFI technical committees, the authors are active members in various engineering and testing organizations, such as ASTM, ASCE, ADSC and PDCA.