Quality Assurance Methods for Risk Reduction in Cast-in-Place Deep Foundation Design and Construction

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ABSTRACT: Modern designs use higher foundation loads, fewer elements, and optimized lengths. Each foundation must therefore meet its load and performance demands. Quality assurance (QA) methods reduce risk by detecting and evaluating design or construction variations. QA methods are presented that check verticality, excavation profile, base cleanliness, concrete quality, concrete cover, and geotechnical capacity of cast-in-place foundations thus improving quality, durability, and performance.

1 INTRODUCTION

For cast-in-place deep foundations, methods can assess deviation from the vertical and deficiencies of the excavation as well as anomalies occurring during the concrete or grout placement process. Quality assurance results for cast-in-place deep foundations are presented that illustrate each method's capabilities. In instances where more than one method can be used, the advantages or limitations of a particular method are presented. Some quality assurance methods feature the added economic benefit that they can be performed remotely with test results provided quickly to the design and construction team. The paper provides engineers and contractors with a resource in specifying and selecting appropriate quality assurance methods for deep foundation risk reduction as well as satisfying regulatory or project quality assurance requirements.

2 VERTICALITY AND EXCAVATION PROILE

The verticality and profile of circular bored piles or rectangular diaphragm wall panels or barrettes is important for a variety of reasons including avoiding concentration of base loads in pile groups, eccentric foundation loading, alignment of foundation and superstructure reinforcement, seismic response, and leakage through diaphragm wall joints. Verticality specifications from assorted international codes are summarized in Table 1. These specifications typically require verticality to be within 1 to 2 % of plumb for bored piles and within 0.4 to 1.0% of plumb for diaphragm walls.

Some bored pile rigs and diaphragm wall cutters can monitor excavation verticality but cannot assess the final excavation profile. For these reasons, verticality and profile checks are often performed post excavation with ultrasonic profiling devices such as the Kelly bar mounted SHAPE® system shown in Figure 1. The device scans the excavation sidewalls at a rate of 1 scan per second as it transits down and up the excavation resulting in an excavation profiling rate of approximately 0.3 m per second. Devices are available for profiling either wet and dry excavations using multi-channel ultrasonic (wet) or lidar (dry) sensors. Winch deployment systems are also available to limit using construction equipment time. Figure 1 displays data from a scan depth. The calculated wave speed through the drilling slurry at that depth is displayed (bottom) along with the eight corresponding received ultrasonic signals in the circular bored pile section. Example verticality

Table 1. Summary of Verticality Requirements for Bored Piles and Diaphragm Walls

Specification, Code or Standard	Verticality
AASHTO LRFD Bridge Construction Specifications, 4th Edition, (2017)	within 1.5% of plumb in soil (bored piles) within 2.0% of plumb in rock (bored piles)
ICE Specification for Piling and Embedded Walls (2017)	within 1.33% of vertical (bored piles) within 1.0% of vertical (walls w/cable grab) within 0.7% of vertical (walls w/ hydraulic grab) within 0.4% of vertical (walls w/ reverse circulation mill)
Eurocode EN 1536:2014 (2014)	within 2% of vertical (bored piles)
Australian Standard AS-2159-2009 (2009)	within 1% of vertical (bored piles)
Indian Standard IS 2911-1-2 (2010)	within 1.5% of vertical (bored piles)

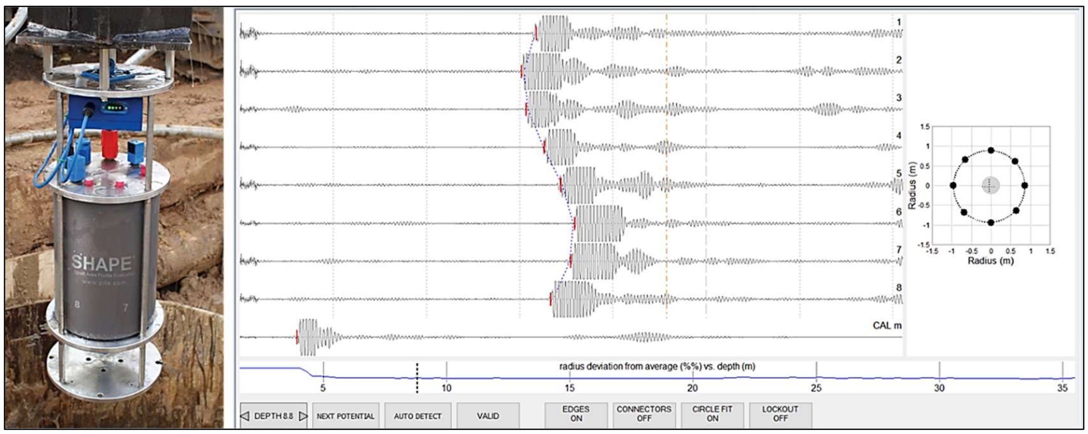

Figure 1. SHAPE® ultrasonic profiling equipment (left) and test signals at one depth (right).

results for a bored pile as well as for the long axis of a 3.0 m x 0.6 m diaphragm wall panel are presented in Figure 2. Note the bored pile verticality results exceed most specification limits presented in Table 1 due to a drilling rig initialization error during setup. Verticality and excavation profile tests can be conducted by an engineer on site or remotely if cellular service is available.

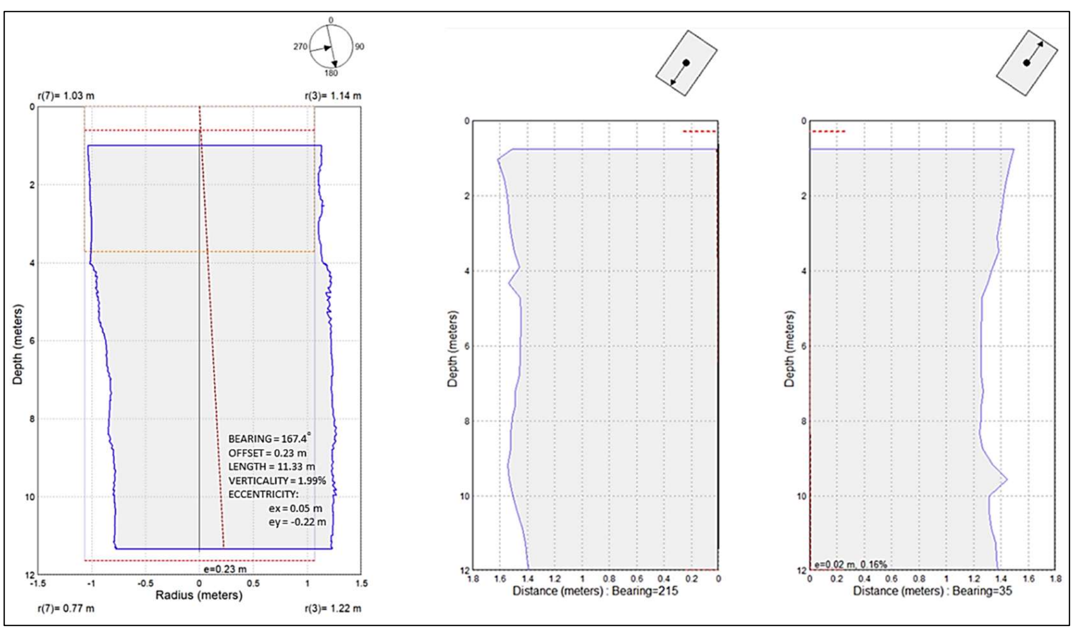

Figure 2. Example test results for bored pile (left) and diaphragm wall panel (center and right)

3 BASE CLEANLINESS

The base cleanliness of bored piles is also an important risk reduction measure to minimize concrete contamination during placement. Post construction settlement issues arising from excessive soft or loose debris left at the base of the foundation excavation can also be avoided. Base cleanliness specifications from assorted international codes are summarized in Table 2. These specifications range from sediment limitations of 13 to 75 mm depending upon the construction technique and geotechnical support condition to generalized and unquantified limits.

Table 2. Summary of Base Cleanliness Requirements for Bored Piles

Specification, Code or Standard	Base Cleanliness
AASHTO LRFD Bridge Construction Specifications, 4th Edition, (2017)	Dry drilled in soil < 38 mm of sediment / loose material. Wet drilled in soil < 75 mm of sediment / loose material. Drilled in rock < 13 mm sediment over 50% of base area.
Eurocode EN 1536:2014 (2014)	Disturbed soil, debris or any other material that could affect the bored pile performance shall be removed from the base prior to concrete placement.
Australian Standard AS-2159-2009 (2009)	Bored piles shall be founded in and underlain by material such that the strength and serviceability design criteria are satisfied.
Indian Standard IS 2911-1-2 (2010)	If borehole stabilized by drilling mud, the bottom of the hole shall be cleaned of all loose and undesirable materials before commencement of the concrete pour.

Base cleanliness checks are performed before commencing concrete placement. One device often used for these assessments is the Kelly bar mounted SQUID™ system shown in Figure 3. The 650 mm wide hexagonal device has three 1000 mm^2 penetrometers and three 150 mm O.D. contact plates. When positioned at the base of the excavation, the penetrometers are pushed into the base materials. A penetrometer force vs displacement plot is obtained from each penetrometer and contact plate. Debris sediment and loose materials are typically defined as having a minimum penetration resistance greater than 0.089 kN which is a commonly defined debris threshold, DTH. Natural soils at the base are defined as having a penetration resistance greater than 0.71 kN which is the penetration resistance threshold, PTH. The measured contact plate displacement between the DTH and PTH thresholds is the calculated debris thickness at each penetrometer location. Base cleanliness tests can be performed by an engineer on site or remotely via cellular service.

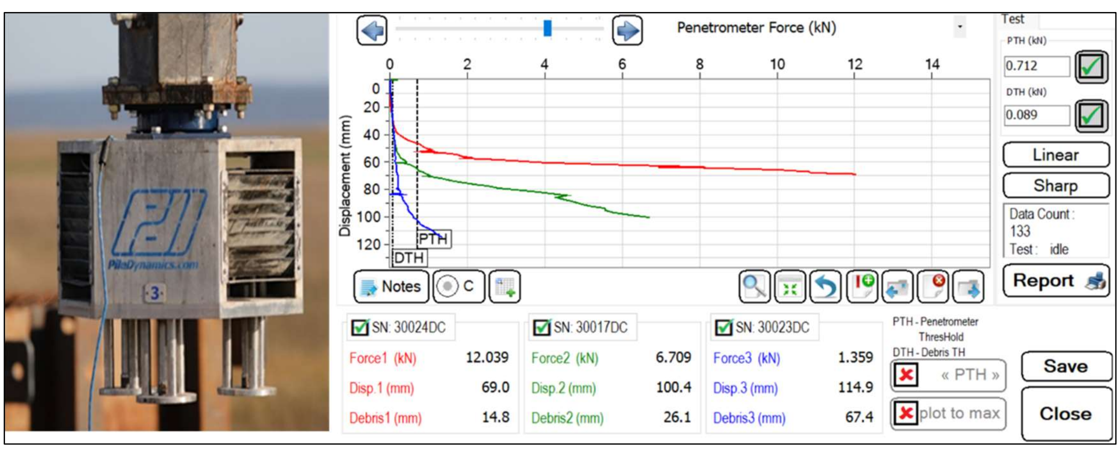

Figure 3. SQUID device (left) and base cleanliness test results (right)

Base cleanliness test results for a wet drilled bored pile on soft rock are included in the right side of Figure 3. These results indicate the debris thickness ranges from 14.8 to 67.4 mm with all results exceeding the Table 2 maximum debris limit of 13 mm over 50% of the base area. Therefore, the base cleanliness is unacceptable and further base cleaning is required before concrete placement. In specifications without values, base cleanliness acceptance or rejection would be less straight forward and more controversial.

4 INTEGRITY AND COVER

Several integrity testing methods are available to reduce the risk associated with undetected structural defects. The ability of the methods to quantity the location and magnitude of an anomaly varies as does a method's ability to ascertain whether it is inside or outside the reinforcing cage. Common methods listed in order of highest to lowest resolution ability include thermal integrity profiling (TIP), crosshole sonic logging (CSL), and low strain pile integrity testing (PIT). Table 3 provides a brief overview of these integrity testing method capabilities and limitations.

Table 3. Integrity Testing Method Advantages and Limitations

Test Method	Advantages	Limitations
Thermal Integrity Profiling (TIP)	Results are available quickest after casting. Full area assessed including cage cover. Remote cloud-based test capability. 3D and slice tomography results. No depth limitations	Must install wires before casting. Can test only during curing. Need accurate volume for temperature to effective radius ratio.
Crosshole Sonic Logging (CSL)	Checks concrete inside cage. 3D tomography for quantifying anomalies. No depth limitations. Can test at any time after curing.	Access tubes required in concrete. Cage cover not evaluated. Tube debonding and bleed water effects can be problematic.
Pile Integrity Testing (PIT)	No advanced planning for wires or tubes. Quickly test numerous foundations. Can test at any time after curing. Minimal site support. Economical.	Difficult to quantify affected area. Assumed wave speed effects length or location assessments. Depth limitation to ~ 30 L/D +/-. Lower defects can be masked. Cracks and joints block signals.

Thermal integrity profiling consists of attaching Thermal Wire® cables to the reinforcing cage prior to its insertion into an excavation or grout filled hole. Each wire includes a temperature sensor every 300 mm along the cable length. On circular foundations, one cable is used for every 300 mm of diameter. For other rectangular elements, wires are paired on opposite faces. After placement, purposely built data loggers attached to each wire upload the data to the cloud or store the data on-site. The resulting temperature versus depth profiles can be used to assess zones with weak concrete or inclusions (cooler temperature), bulges (higher temperature), cage shifting, (opposite wire temperatures), and effective radius and cover (based on placed volume and average temperature). For typical foundation sizes, these assessments can be made within 24 to 48 hours of casting making it the quickest integrity assessment method available after casting.

A photo of TIP wires attached to a reinforcing cage each with a data logger is shown in Figure 4. Results of temperature vs depth (center) and a plot of effective radius and concrete cover vs depth (right) from a different 3.0 m diameter, 38.4 m long bored pile are also presented in Figure 4. A significant anomaly is apparent by the drop in temperature at 27 m in the temperature vs depth plot. The effective radius vs depth plot indicates the defect exceeded the acceptance criteria proposed by Piscsalko et al., (2016) with more than a 6% reduction in effective radius. A 6% reduction in effective radius may correspond to a 6% reduction in circumference (geotechnical resistance), a 12% reduction in section area (compressive resistance) and a 22% reduction in moment of inertial (bending resistance). Subsequent concrete cores confirmed a significant defect requiring remediation. TIP data analysis was performed at the ½ peak temperature which was reached 38 hours after concrete placement in the 3 m diameter shaft. For additional insight into thermal integrity testing refer to Belardo, et al., (2021).

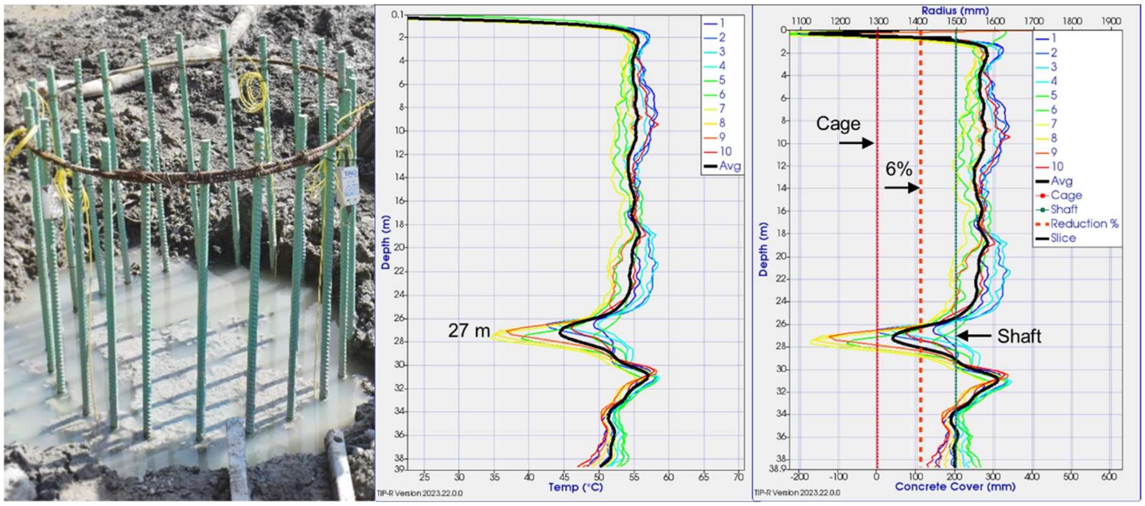

Figure 4. TIP Wire Installation (left), Temperature Profile (center), and Effective Radius Results (right).

Crosshole sonic logging (CSL) consists of attaching steel or PVC access tubes to the reinforcing cage before cage insertion into a bored pile, barrette, or slurry wall panel excavation, and prior to concrete placement. For circular foundations, one access tube is used for every 300 mm of diameter and for other rectangular elements tubes are paired on opposite faces. Immediately after placement, the access tubes are filled with water to minimize thermal decoupling of the tube from the surrounding concrete. A minimum of three to seven days after casting, transceivers are lowered to the base of the access tubes and then raised at a rate of up to 1.5 m/s. Signals, acquired at 32 scans/s, provide a vertical testing resolution of 1 cm. The resulting first arrival time (FAT) and signal energy versus depth profiles can be used to assess zones with weak concrete or soil inclusions (delayed arrival).

A four probe CSL setup is pictured on the left side of Figure 5. The calculated concrete wave speed (based on the FAT and the tube spacing above grade) and the signal energy strength are presented in the center of Figure 5 with the associated waterfall diagram for that tube pair shown to the right. The left edge of the waterfall plot is the first arrival time. This profile is very consistent over its 20.25 m length except over the final 0.5 m above the pile toe where an anomalous zone is indicated by a 72% delay in FAT and the 14 dB reduction in signal energy. This anomalous zone was found in essentially all CSL profiles. In 2019, the Deep Foundations Institute published

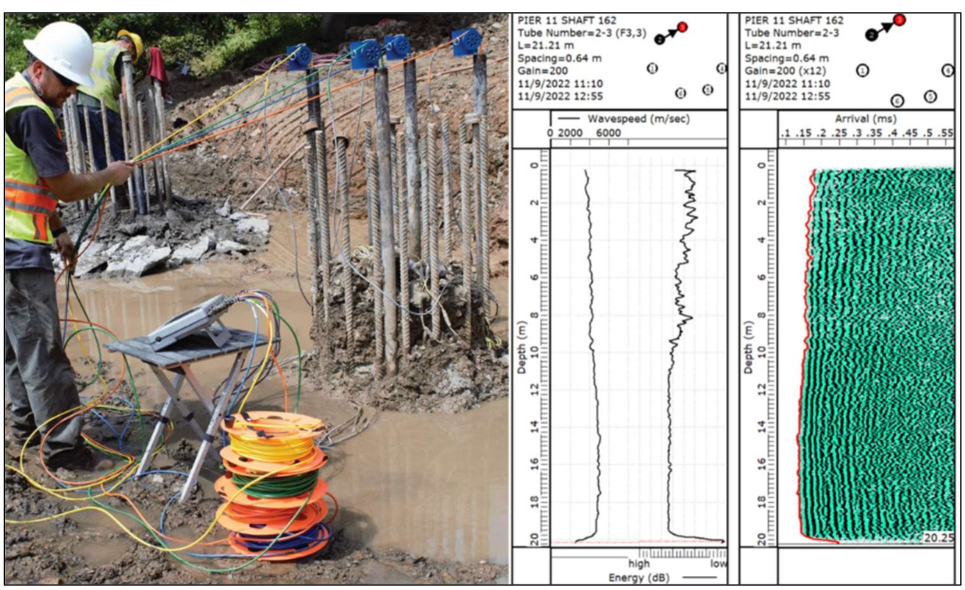

Figure 5. CSL test setup (left), Wave Speed and Energy vs Depth plots (center), and FAT plot (right).

a white paper on CSL evaluation criteria which should be consulted for insight into foundation evaluation based on CSL results. In accordance with the DFI criteria, the results at the base of this 1.9 m diameter, rock socketed bored pile were classified as Class C, highly abnormal CSL test results. A tomography analysis was performed to quantify the affected area and a dynamic load test was used to substantiate the pile satisfied the loading demand and performance requirements.

Another integrity test method is the low strain pile integrity test (PIT). In this test, a small handheld hammer is used to strike the top of the pile while the pile response to the low strain impact is monitored by an accelerometer placed atop the pile head. The recorded acceleration is integrated over time resulting in a velocity vs time record. Multiple impacts are taken and averaged to eliminate spurious influences on the collected signals. Exponential amplification is applied over the lower 80% of the test record to compensate for signal decay. Records with no significant reflections prior to the toe reflection indicate a continuous pile with no significant anomalies or defects. Reflections occurring prior to the toe reflection can indicate planned cross-sectional changes such as a rock socket or unplanned changes such as bulges, necks, inclusions, or other concrete defects. The concrete or grout must be cured, preferably for 7 days, before the test is performed.

A low strain integrity test in progress is shown in Figure 6. A test record of velocity vs time for a 2.74 m diameter by 11.28 m long bored pile is also presented. A major defect is indicated at 7.1 m below the pile head based on the magnitude of the positive refection. Additional insight into low strain integrity testing methods can be found in Deep Foundations Institute (2012) Auger Cast-In-Place Pile Committee.

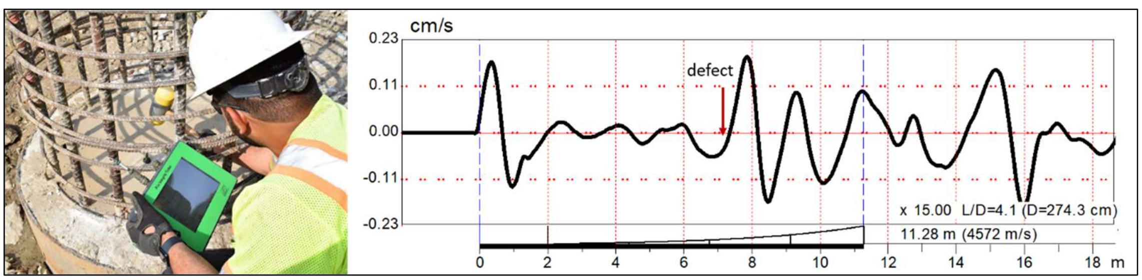

Figure 6. Low strain pile integrity test (left) and example velocity vs time test record (right).

5 GEOTECHNICAL CAPACITY

Several load testing options are available to check that the requisite capacity has been achieved and thereby reduce the risk associated with unacceptable foundation performance. The accuracy and reliability of a load testing method varies along with the cost of the testing methods. Common methods include static load testing, bi-directional static load testing, and dynamic load testing. Table 4 provides a brief overview of each method’s advantages and limitations for assessing axial compressive capacity.

Static load testing is generally considered to be the most accurate method of axial compressive capacity determination since the foundation is loaded from the top down while the applied load and associated movement are recorded. Static load tests can be performed by jacking against a reaction beam anchored by reaction piles or against a weighted platform supported by cribbing. Depending upon the magnitude of the required load, this can result in a static load test being very expensive for heavily loaded foundations. A typical static load test setup and axial compressive test result are shown in Figure 7. The assigned failure load of 1900 kN is determined by where the load-movement plot crosses the Davisson failure criterion line. Kodsy et al., (2022) provides details for this method as well as eight other static load test interpretation criteria for the geotechnical capacity assessment of drilled deep foundations.

Test Method	Advantages	Limitations
Static Load Testing	Considered most accurate method.	Often the most expensive method. Limited by reaction capacity.
Bi-Directional Load Testing	Only method for very high capacities. No reaction frame at the surface. Most economical for high capacities.	Jacks must be cast into pile. Full resistance not achieved. Pile remediation required if reused.
Dynamic Load Testing	Limited advanced planning required. Economically test several foundations. Can test production foundations.	Capacity from signal matching. Limited by mobilized resistance. Dynamic effects must be analyzed.

Table 4. Axial Compressive Capacity Testing Methods Advantages and Limitations

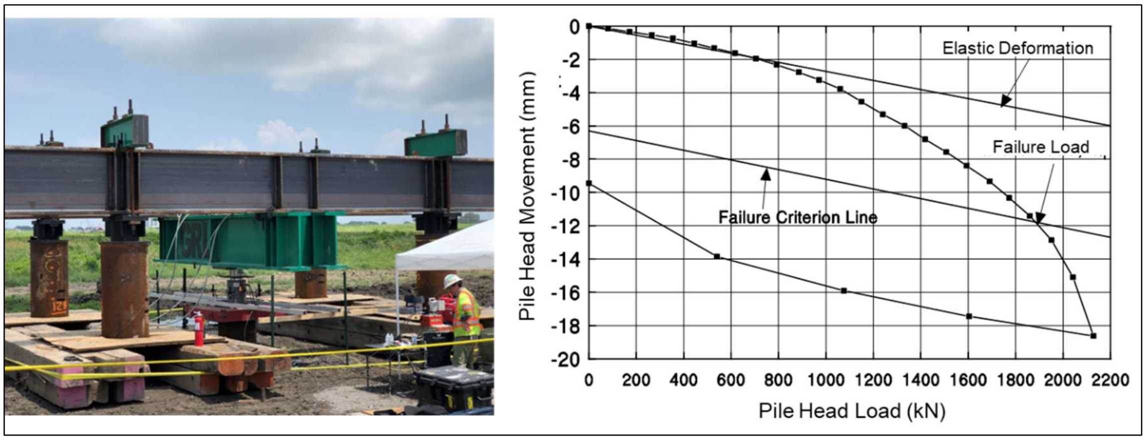

Figure 7. Compression static load test with reaction piles (left) and interpreted load-movement result (right).

When static load test requirements exceed 5 to 10 MN for cast-in-place foundations, a bi-directional static load test is a commonly used alternative to a conventional top-down static load test. A single or multiple jack assembly is attached to the element reinforcement and cast into the deep foundation. Once the concrete or grout has reached the required test strength, the jack assembly is pressurized, loading the foundation both upward and downward from the jack assembly location. Rarely is the full geotechnical resistance above and below the jack assembly simultaneously reached. The test is frequently terminated at a conservative lower bound capacity when the geotechnical resistance either above or below the jack assembly is achieved. A typical multi-jack test setup and a test result are shown in Figure 8. The full geotechnical resistance is greater than the 68.6 MN of applied load due to the limiting movement of 14 mm occurring above the jack. For additional information on bi-directional load testing, refer to Schmertmann & Hayes (1997).

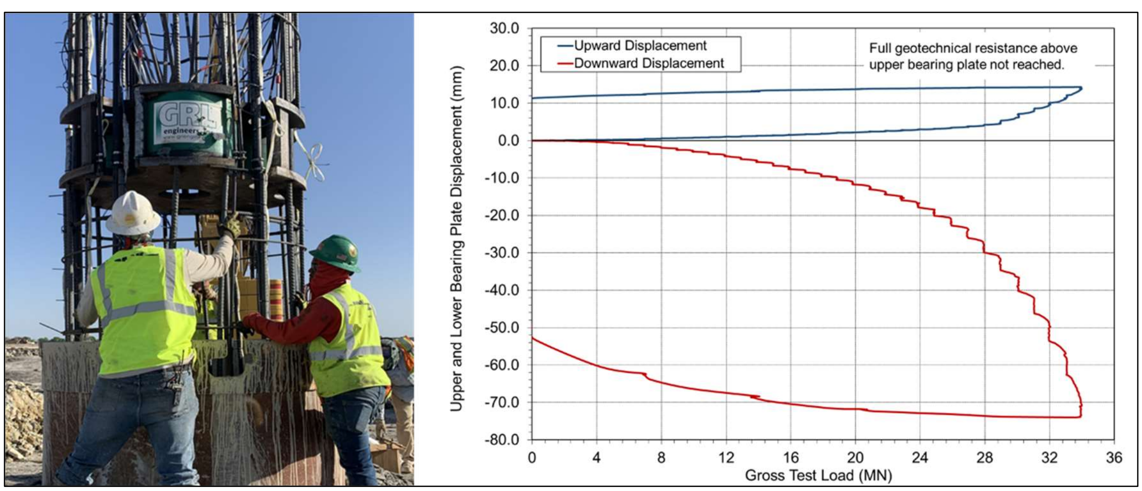

Figure 8. Cage with multiple bi-directional jack assembly (left) and load-movement result (right).

Dynamic load tests are another cost-effective means of evaluating the geotechnical capacity of cast-in-place foundations. The minimum required ram weight to mobilize the geotechnical resistance is typically 1% of the required capacity in rock and 2% in soil. On the order of 3 to 5 impacts are typically applied with the drop height gradually increased. Force and velocity records are acquired and processed using a Pile Driving Analyzer DLT system. Improved test quality can be obtained by using a pile top force transducer thereby mitigating problematic strain measurements due to lower quality concrete or poor concrete surface conditions near the pile head. CAPWAP signal matching analyses, Rausche et al. (2010), are typically performed on each blow to develop a load-displacement envelope and assess geotechnical capacity. An example of a 427 kN drop weight including a pile top force transducer and processed test results is presented in Figure 9. Refer to Hussein et al. (2008) for details on dynamic load testing of cast-in-place foundations.

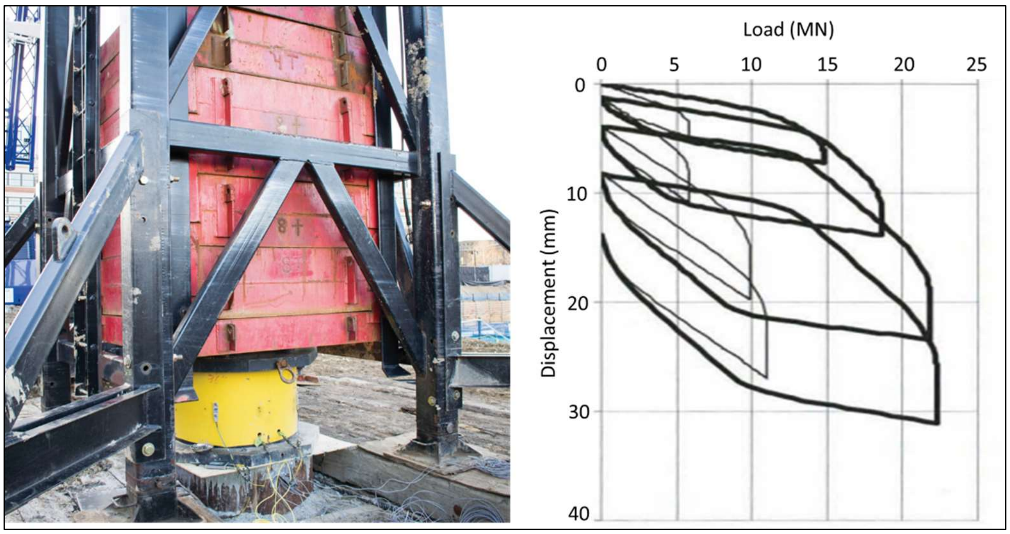

Figure 9. Drop weight with top transducer (left) and CAPWAP load-displacement envelope (right).

6 CONCLUSIONS

Several quality assurance methods and their results have been presented to illustrate method capabilities. The presented examples identified where internal drill rig instrumentation did not correctly assess verticality, where base cleanliness tests were essential to good construction, where concrete anomalies and cover concerns were detected by post concrete placement integrity methods, and where the geotechnical capacity was documented through static or dynamic load tests. Advantages and limitations of integrity and capacity methods have been reviewed. Test method examples reaffirm the need for independent quality assurance methods to reduce design and construction risk as well as improve quality and durability of cast-in-place deep foundations.

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