Yerinde Dökme Derin Temellerde Kalite Güvence Metotları

QUALITY ASSURANCE METHODS FOR CAST-IN-PLACE DEEP FOUNDATIONS

ÖZET

Yerinde dökme derin temeller, ağır yük taşıyan yapıları desteklemek için yaygın olarak kullanılmalarının yanı sıra, yüzeyi zayıf zeminli bölgelerde, deniz ortamlarında veya deprem, erozyon, veya diğer olağanüstü olaylara maruz kalması beklenen bölgelerde inşa edilen yapıları desteklemek için de kullanılmaktadır. Ekonomik faktörler, daha yüksek derin temel yükleri için, daha az derin temel elemanına ve optimize edilmiş derin temel uzunluklarına yol açmıştır. Bu nedenle, her derin temel elemanının, tasarlanan hizmet ömrü boyunca yük taşıma ve performans gereksinimlerini karşılaması gerekmektedir. Kalite Güvencesi (KG) yöntemleri, tasarım veya inşaat sırasındaki farklılıkların tespiti ve bu farklılıkların değerlendirmesi yoluyla, derin temel imalatındaki olası riskleri azaltmak için kolaylıkla uygulanabilir. Yerinde dökme beton temellerde uygulanan KG yöntemleri ile, kazı eğimi ve profili, taban temizliği, beton kalitesi ve sürekliliği, pas payı ve geoteknik kapasite gözden geçirilir. Sunulan yöntemlerin avantajları ve limitleri gözden geçirilir. Bu sunum, mühendislere ve müteahhitlere, derin temel imalat risklerini azaltmak için uygun KG yöntemlerini belirlemede veya seçmede yardımcı olmasının yanı sıra mevzuat veya proje KG gereksinimlerini karşılamaya da yardımcı olacaktır.

Anahtar Kelimeler: Kalite Güvencesi, Temeller, Risk Azaltma, Bulut tabanlı

ABSTRACT

Cast-in-place deep foundations are widely used to support heavily loaded structures, and structures constructed in areas with weak surficial soils, in marine environments, or subjected to seismic, scour, or other extreme design events. Economic considerations have resulted in higher deep foundation loads, fewer deep foundation elements, and optimized deep foundation lengths. Therefore, each deep foundation element must satisfy its load support and performance requirements over the intended service life. Quality assurance (QA) methods are readily available to reduce deep foundation risk by detection and evaluation of design or construction variations. For cast-in-place foundations, the advantages and limitations of QA methods will be reviewed which assess excavation verticality and profile, base cleanliness, concrete quality and integrity, concrete cover, and geotechnical capacity. The presentation will assist engineers and contractors in specifying or selecting appropriate QA methods for deep foundation risk reduction as well as satisfying regulatory or project QA requirements.

Key Words: Quality Assurance, Foundations, Risk-Reduction, Cloud-based

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1. INTRODUCTION

All deep foundations require quality control and assurance tests on the constructed and installed foundation. Driven piles are subject to manufacturing controls at the plant and installation controls during driving. Cast-in-place foundations have additional inherent uncertainties particularly when they are excavated and concrete filled under wet or slurry construction techniques. These uncertainties necessitate quality assurance tests for excavation verticality and profile, for base cleanliness checks on debris removal during cleanout, for structural integrity assessment following concrete placement, and for capacity documentation for the proposed structure loads. Therefore, quality assurance tests for cast-in-place foundations must be performed in the field during their excavation as well as during and after the concreting process.

2. VERTICALITY AND PROFILE

Cast-in place foundations must meet verticality and profile requirements to satisfy the design intent. Maintaining verticality within the specified limits is important to avoid introducing large bending moments or shear forces in a misaligned foundation not structurally designed to accommodate them. Similarly, a foundation profile differing from designed can alter the expected performance or loading under seismic or downdrag conditions. For bored piles, verticality requirements of 1.0 to 2.0% are common. For embedded walls, verticality requirements of 0.4 to 1.0% are typical. Some rigs can monitor excavation verticality but they cannot determine the final profile.

One commonly used device that can assess both verticality and profile is the Shaft Area Profile Evaluator or SHAPE® system. It scans bored pile or diaphragm wall excavation sidewalls at a rate of 1 scan per second as it transits down and up the excavation. The SHAPE unit can be attached to a drill rig Kelly bar or operated independently using a winch system. Depending on the deployment mechanism, this results in a profiling rate of approximately 0.3 m per second. SHAPE systems are available for either wet or dry excavations utilizing multi-channel ultrasonic (wet) or lidar (dry) sensors.

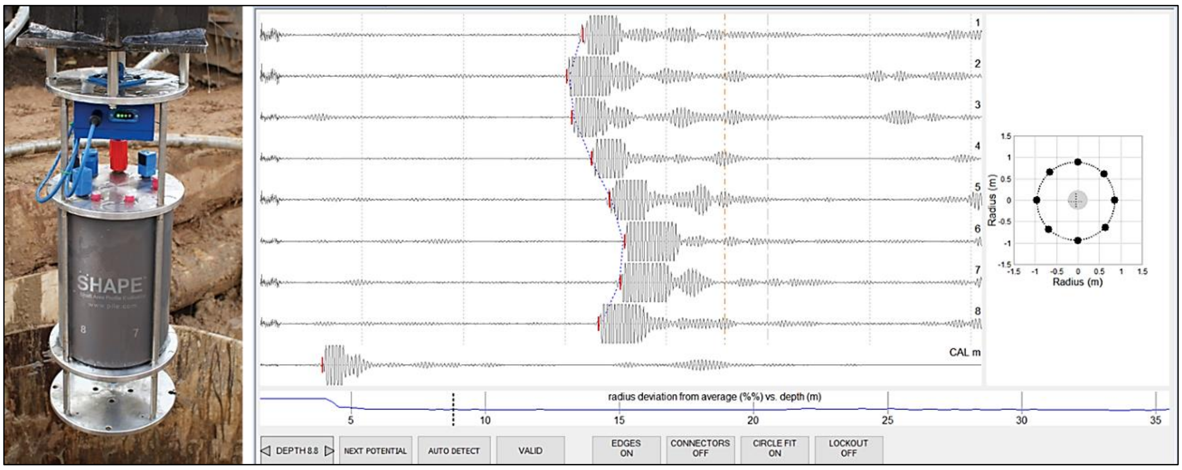

Figure 1. SHAPE device (left) and test results at one test depth from each sensor (right).

Figure 1 shows a SHAPE device for a wet excavation mounted to a Kelly-bar adapter. At incremental test depths, each sensor records the signal arrival time reflected from the excavation sidewall. Sidewall reflection results recorded by each of the eight sensors at the test depth are displayed (right). These results are then compiled in profile sections of the radius versus depth oriented at 0-180°, 45-225°, 90-270°, and 135-315° slices.

Results of a bored pile constructed in slurry are presented in Figure 2. The maximum eccentricity profile (left) denotes an eccentricity of 0.21 m. Bulges are apparent near the 13.5 and 16.5 m depths. The effect of the bulges on the excavation volume vs depth plot (right) is evident by the divergence from the theoretical volume starting near the 17.3 m depth. The offset plot (center) notes the excavation drifts to the northwest with a bearing of 310.5 degrees. The verticality of 0.84% is within the project specification limit of 1.5%.

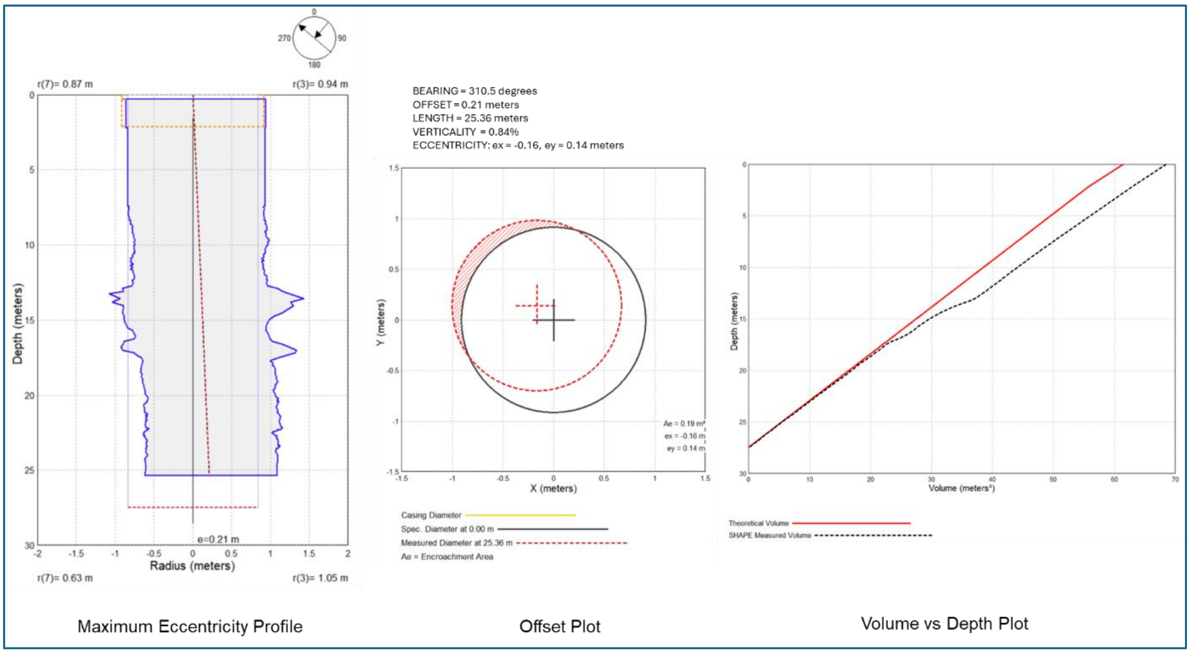

Figure 2. SHAPE profile, offset, and volume vs depth plot in shaft with sidewall instability.

SHAPE results on a nearby bored pile drilled in similar soils by a different foundation contractor are presented in Figure 3. Those results illustrate the more uniform installation resulting from improved drilling procedures and slurry controls. The resulting bored pile had a maximum eccentricity of 0.06 m, a verticality of 0.24%, and a SHAPE calculated volume close to planned.

3. BASE CLEANLINESS

The base cleanliness of a bored pile, barrette, or diaphragm wall excavation is also very important to its performance under load and should be evaluated prior to concrete placement. Debris remaining at the excavation base can be displaced during the concrete pour, become trapped within the element, and creating zones of weak or contaminated concrete. Historically a weighted measuring tape was used to crudely assess base cleanliness conditions. More recently, electronic devices such as the Shaft Quantitative Inspection Device (SQUID™) shown in Figure 4 have been incorporated into project specifications to provide a more quantitative assessment. SQUID can be mounted to the

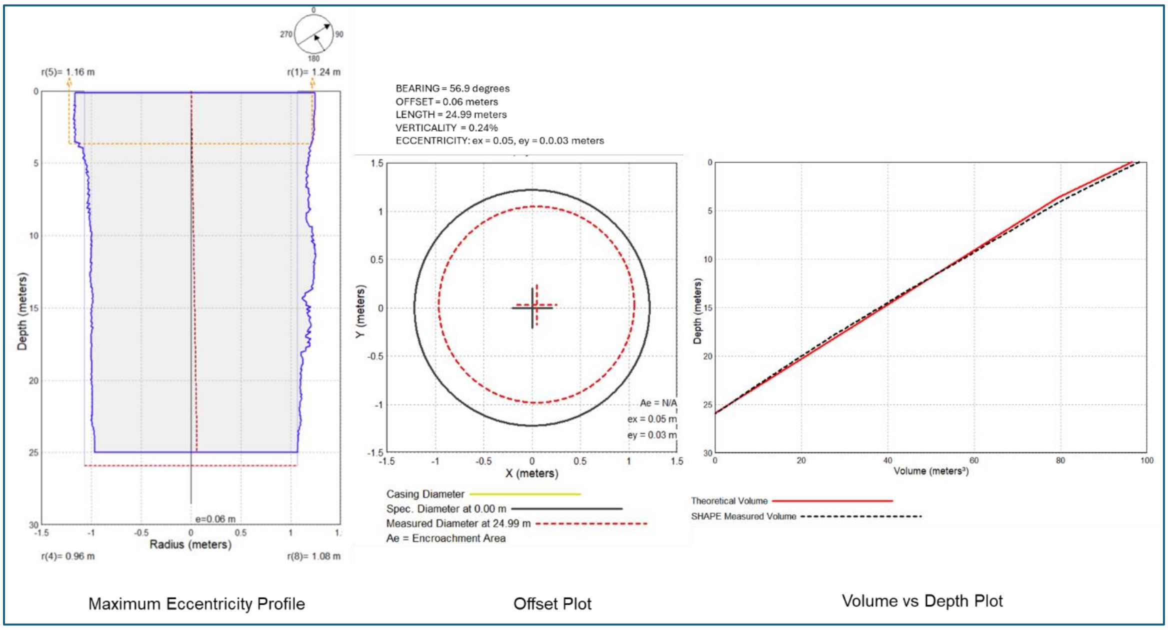

Figure 3. SHAPE profile, offset, and volume vs depth plot for well controlled installation.

drill rig Kelly-bar or to a crane line with a suitably weighted device. The number of test locations are determined based on the foundation size.

SQUID has a 650 mm wide hexagonal shape with three 1000 mm^2 penetrometers that measure applied force. The penetrometers pass through the center of three 150 mm O.D. contact plates measuring the movement associated with the measured penetrometer force. Base cleanliness is evaluated from the measured force versus displacement plots. Moghaddam, etal. (2018) used bearing capacity theory to define debris and loose materials as having a penetration resistance less than 0.089 kN. This has been commonly adopted as the debris threshold, DTH. Similarly, natural soils at the base were defined as having a penetration resistance greater than 0.71 kN which is commonly used as the penetration resistance threshold, PTH. The calculated debris thickness at each penetrometer location is the measured contact plate displacement between the DTH and PTH thresholds. These

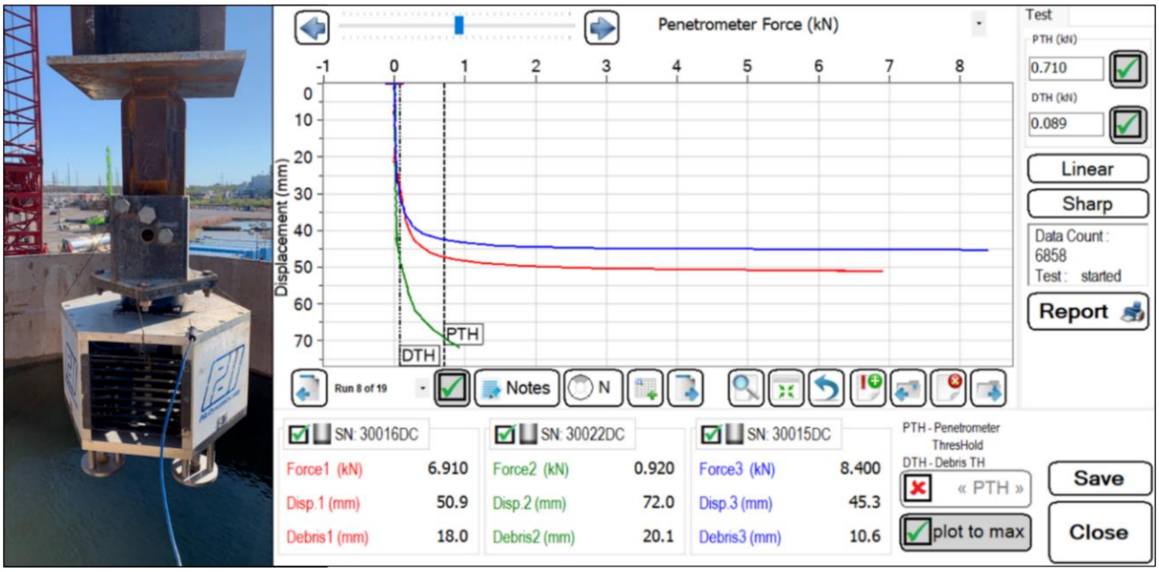

Figure 4. SQUID system attached to weighted beam on crane line (left) and test results (right).

thresholds can be adjusted if local codes or specifications stipulate other values. Figure 4 shows the debris thickness ranged from 10.6 to 20.1 mm with an average of 16.9 mm.

4. CONCRETE INTEGRITY AND COVER OF CAST-IN-PLACE FOUNDATIONS

Several methods are available to assess the structural integrity of cast-in-place foundations. In order of the foundation section coverage and resolution accuracy from high to low these include Thermal Integrity Profiling (TIP), Crosshole Sonic Logging (CSL), and Pile Integrity Testing (PIT). An overview of the advantages and limitations of each method are presented in Table 1.

Table 1. 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. Low heat cement can limit use.
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 anomaly area. Assumed wave speed effects length and depth assessments. Depth limitation to ~ 30 L/D +/-. Lower defects can be masked. Cracks and joints block signals.

4.1 Thermal Integrity Profiling (TIP)

Thermal Integrity Profiling consists of attaching Thermal Wire® Cables onto a foundation's reinforcing cage prior to cage pickup and insertion into the foundation excavation. Each thermal wire has a thermal sensor every 300 mm along its embedded length. These wires provide temperature versus depth profiles that can be used to assess zones with weak concrete or inclusions (cooler temperature), bulges (higher temperature), cage shifting, (opposite wire temperatures), and on circular foundation elements the effective radius and concrete cover (based on placed volume and average temperature).

For circular elements, one thermal wire is typically used for each 300 mm of pile diameter. The wires are equally spaced around the perimeter with each wire attached adjacent to a longitudinal bar inside the lateral hoop steel. For barrettes or diaphragm wall panels, the thermal wires are attached in a similar manner with wire pairs on opposite perimeter faces. The maximum distance between perimeter wire locations is typically limited to 600 mm. Thermal wires in circular and rectangular elements are usually placed in diametrically or exterior opposite pairs so that shifting of the reinforcing cage and concrete cover can be assessed. When long reinforcing cages are constructed in sections, thermal wires are attached to each section and then quickly spliced.

Within a few hours of completing the concrete pour, data loggers are attached to each Thermal Wire cable to sense the heat of hydration to assess integrity. Once data loggers are attached, thermal data can be pushed to the Cloud for real-time monitoring of the curing process. The data can also be downloaded from the data loggers onsite if cellular service is not available. For typical foundation sizes and concrete mixes, integrity assessments can be made within 24 to 48 hours of casting making the TIP method very attractive to construction schedules.

Figure 5 presents a photo of a bored pile with four thermal wires attached to the reinforcing cage and specialty-built data loggers attached atop each wire. The center plot presents temperature versus depth results for each wire as well as the average from all wires. These temperatures plots have a top and bottom rolloff due to the additional temperature losses from the top surface to the air and base to the soil. In the right plot, rolloff corrections have been applied at the top and bottom of the shaft to convert the temperature plots to effective radius plots based on the average temperature and placed concrete volume.

Piscsalko et al. (2016) proposed the widely used TIP integrity evaluation criterion based on the effective radius vs. depth plot. In that criterion, a defect is indicated if there is more than a 6% reduction in effective radius. On a circular section, a 6% reduction in effective radius corresponds 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). The TIP results in Figure 5 indicate a significant anomaly near the pile toe based on the significant drop in effective radius vs. depth plot starting near 12.0 m. The effective radius plot indicates the defect exceeds a 6% reduction near 12.6 m and extends further inside the reinforcing cage at 13.3 m. For additional details on the thermal integrity profiling method and interpretation procedures, refer to Belardo et al. (2021).

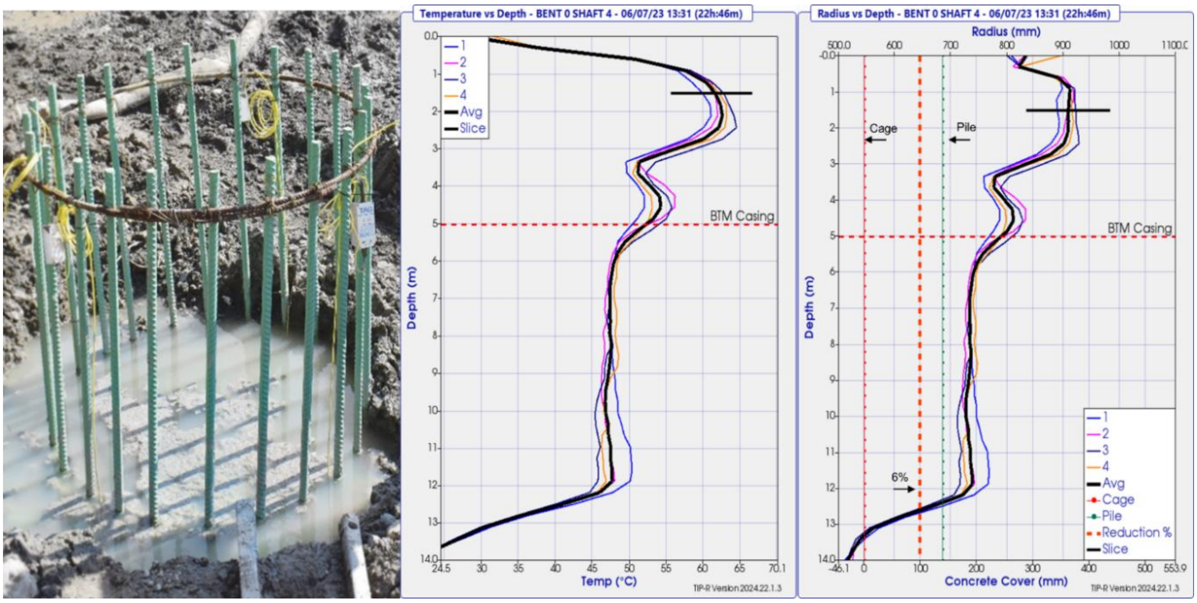

Figure 5. TIP equipment (left), temperature vs depth (center) and effective radius vs depth (right).

Thermal integrity profiling can also be used on rectangular barrette and diaphragm wall elements. Figure 6 presents TIP results from all 14 thermal wires installed on a 6.65 m wide by 0.84 m deep panel with an embedded length of 21 m. TIP software allows the presentation of all wires, both side wall faces, just the excavation side face, just the earth side face, or just the corner locations to be displayed and evaluated. In all wire plots shown in Figure 6, the excavation wall face consisting of wires 10, 11, 12, 13, and 14 each exhibit temperature increases near 4.0 and 6.5 m indicative of bulges at those depths.

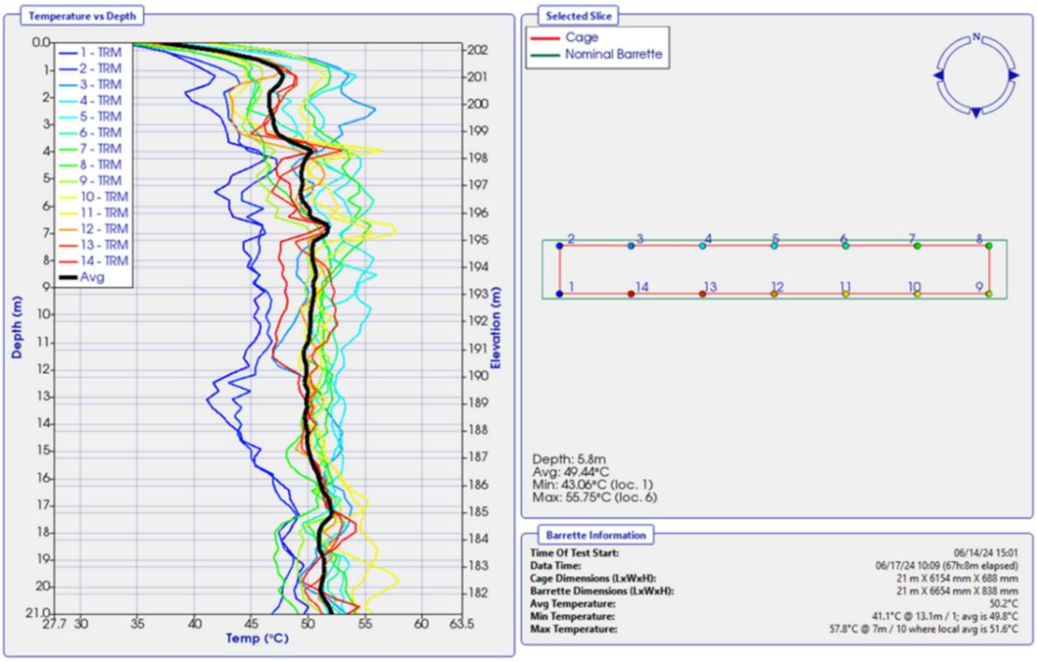

Figure 6. Thermal Integrity Profiling results for all wires in a diaphragm wall.

4.2 Crosshole Sonic Logging (CSL)

Crosshole Sonic Logging is also used to evaluate the integrity of cast-in-place bored piles, barrettes and diaphragm walls. Steel or PVC access tubes are wired to the reinforcing cage prior to cage pickup and insertion into the excavation. The tubes are capped at the top and bottom to prevent debris inflow. Immediately after concrete placement, the tubes must be filled with water to minimize debonding between the tubes and concrete. Testing is typically performed between 3 to 7 days after casting. Ultrasonic probes are lowered to the bottom of the tube pairs and then pulled from the bottom up at a rate of up to 1.5 m/s while maintaining a level horizontal plane between the probes. Signals can be acquired at 32 scans/s providing a vertical testing resolution of 1 cm. An encoder wheel atop the access tubes determines the probe positions as the test is performed. CSL signals are stacked horizontally providing plots of the first arrival time (FAT) and signal energy versus depth profile as well as a waterfall plot noting the first arrival time and signal strength. This data is used to assess zones with weak concrete or soil inclusions.

CSL tests can be performed using a transmitter and receiver probe or using a transceiver probe that both transmits and receives ultrasonic signals. In a bored pile with four access tubes, a four transceiver probe system can test all tube combinations with one pull compared to the six pulls required to test all profiles with a traditional two probe system.

Figure 7 presents a photo of a typical CSL test being performed (left). Illustrative CSL test results for a main diagonal profile on an unrelated pile are also depicted. Note a major issue is apparent in the test results vs. depth plots over the lower 1.2 m of this 14.02 m long bored pile. A complete loss of wave speed and signal energy (center) is apparent, and the first arrival time waterfall plot (right) vanishes beginning near the 12.8 m depth. CSL results

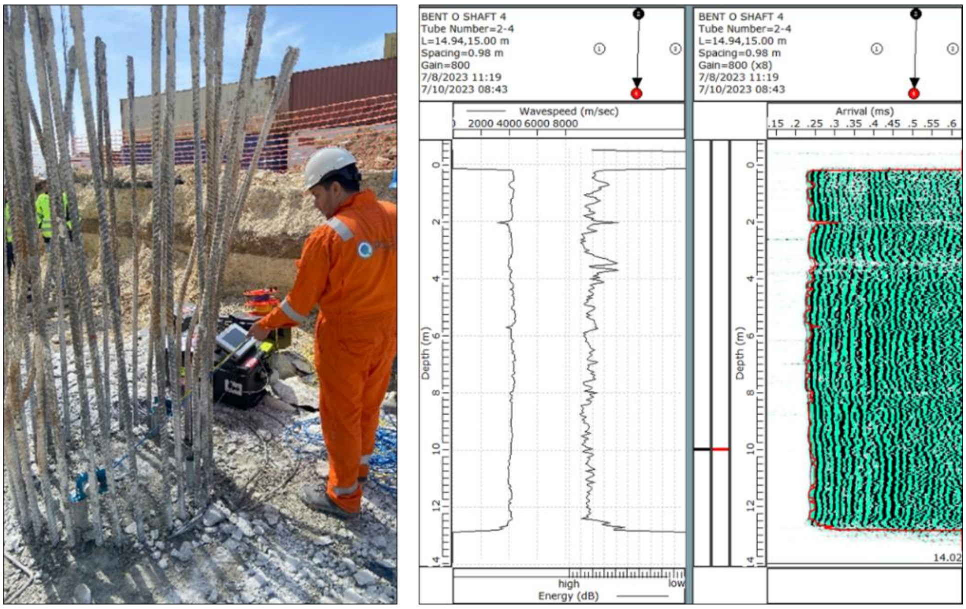

Figure 7. CSL test (left), first arrival time and energy (center) and FAT waterfall (right) vs depth plots.

for all perimeter profiles and the other main diagonal profile had a similar result. In accordance with the Deep Foundations Institute (2019) white paper on CSL result evaluation, this would be a Class C - highly unusual CSL result that would require further evaluation of the foundation. It is interesting to note that the TIP results in Figure 5 and the CSL results in Figure 7 are from the same bored pile. Both integrity methods detected a significant problem at the pile toe. The TIP results indicated the onset of the problem slightly higher since anomalies occurring both inside and outside the cage are detected whereas the anomaly needed to extend into the cage to influence the CSL signal path.

4.3 Low-Strain Pile Integrity Testing (PIT)

Low strain pile integrity testing (PIT) is another method frequently specified. In this test, an impact is applied to the pile head with a small hammer and the pile response is recorded by a surface mounted accelerometer. The acceleration signal is integrated over time resulting in a record of pile top velocity versus time. Multiple impact records are recorded and averaged to minimize spurious effects on test records. A low strain impact decays with depth due to internal pile damping and soil resistance effects. To compensate, exponentially signal amplification is applied over the lower 80% of the pile. A sound pile is indicated by no major reflections occurring prior to the reflection from the pile toe. The sign and magnitude of reflection occurring prior to the toe reflection can be evaluated for necks, bulges, planned diameter changes, or other variations in the cast-in-place element.

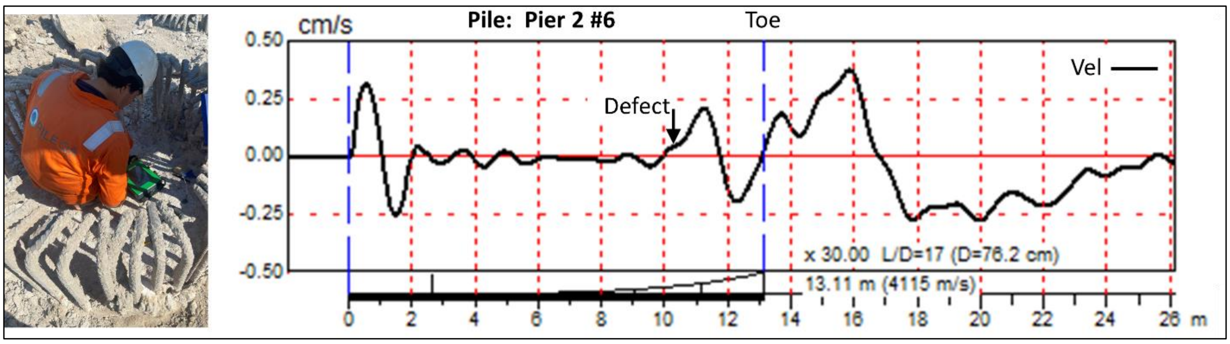

Figure 8. Photo of a PIT test (left) with an example record indicating a defect at 10.2m depth.

A photo of a PIT test and example test result for a 762 mm O.D. bored pile with a defect at 10.2 m is shown in Figure 8.

GEOTECHNICAL CAPACITY

Numerous methods are available to evaluate the geotechnical capacity of a cast-in-place deep foundation under axial compressive load. These include conventional top-down static load tests, bi-directional static load tests, and dynamic load tests. Depending on the required ultimate capacity and site conditions, the number of conventional or bi-directional load tests that can be performed can be cost prohibitive. Dynamic load tests offer a cost-effective way to supplement a load test program and provide additional site coverage.

In a dynamic load test, a weight is typically dropped three to five times onto a cast-in-place foundation element with the drop height increased between impact events. A minimum ram weight of approximately 2% of the required capacity is needed for cast-in-place foundations in soil, and 1% for foundations on rock. A heavier ram weight can be helpful for easier resistance mobilization and lower stress levels within the tested element. During impacts, a PDA-DLT™ system acquires force records from strain gages mounted near the pile head or from a top force transducer placed on the pile top surface. Similarly, velocity records are acquired from accelerometers attached to the pile. The force and velocity records are analyzed with the CAPWAP® program to evaluate the mobilized resistance and pile load bearing capacity.

One of the earliest bored pile projects where dynamic load tests were correlated with static load tests is described by Seidel and Rausche (1984). On that project, both the capacity and load-movement curves obtained from the static and dynamic load tests showed good correlation. Hussein et al. (2008) details test results on a bored pile project where eight piles were dynamically load tested to evaluate foundation capacity concerns. Figure 9 presents a photo of a 14 ton drop weight system conducting a dynamic load test. CAPWAP analyses are generally performed on each impact and plotted consecutively to provide a load-movement envelope; an example of this cumulative blow presentation of CAPWAP load-displacement plots from a different bored pile project is presented on the right side of Figure 9.

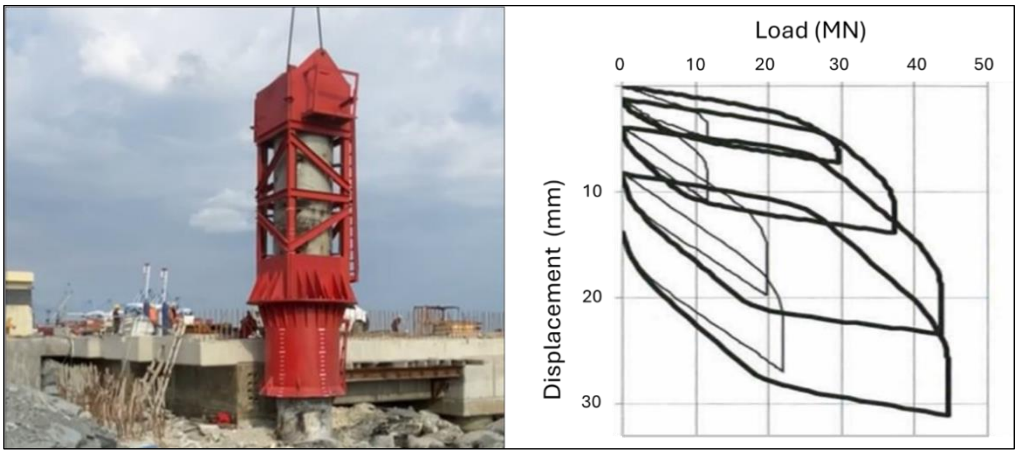

Figure 9. Dynamic load test on bored pile (left) and example test results (right).

6. CONCLUSIONS

Numerous quality control and assurance techniques have been summarized that are readily available to improve cast-in-place foundation quality, durability and performance under load. Several integrity test methods exist for cast-in-place foundations; the testing method selected for a project should consider the particulars of the foundation element itself, foundation redundancy, and a full understanding of the selected method's applicability, advantages and limitations.

7. REFERENCES

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