Advances in Quality Control Methods for Bored Pile and Diaphragm Wall Foundations with Case Histories

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Abstract. Higher loads on deep foundations and more stringent deep foundation performance requirements have increased the need for improved quality control methods. To satisfy the design intent, the as-built shape, vertical alignment, base cleanliness, cage alignment, concrete cover, and concrete integrity are all important. Several new or improved quality control methods are available to check these considerations on bored pile and diaphragm wall foundations. This paper presents an overview of recent advances in quality control devices along with condensed case histories illustrating their use and project application.

1. Introduction

Verticality requirements typically range from 1 to 2% based on local specifications and the bearing materials. The as-built shape and verticality of bored pile / wall excavations can be quickly assessed using a wireless device that sonically determines the excavation radii and from this determines the verticality while advanced at a rate of up to 300 mm per second. The Shaft Area Profile Evaluator or SHAPE device includes two pressure sensors, a calibration sensor, and eight pairs of ultrasonic sensors to determine the depth of the scan, the associated distance to the sidewall, the foundation geometry, and its verticality.

Base cleanliness requirements vary depending upon local specifications and the load transfer mechanism. The presence of too much sediment can compromise the concrete quality or foundation performance. For bored piles drilled under slurry that bear on rock, the sediment at the base is sometimes limited to 13 mm or less. For bored piles bearing on soil, higher sediment thicknesses of 38 mm to 75 mm are frequently allowed. Sediment thickness can be quickly and quantitatively assessed by attaching a device to a drilling machine Kelly bar or other suitable element. The Shaft Quantitative Inspection Device or SQUID utilizes three penetrometers and three debris plates to determine sediment thickness.

Cage alignment, concrete cover, and concrete integrity are all important to the durability and performance of a foundation. These items can be evaluated by embedding thermal sensors into the concrete using Thermal Wire® cables. The number of Thermal Wire cables required in a foundation is dependent upon the foundation size and geometry. These cables have sensors every 300 mm along their embedded length and can quickly evaluate concrete integrity, reinforcing cage alignment, and concrete cover. Thermal Integrity Profiling assessments of concrete integrity can generally be performed much sooner than other available methods by using Cloud technology and thereby reducing integrity testing impacts on construction schedules.

2. Verticality Requirements.

Verticality requirements for bored piles and diaphragm walls vary by local practice and specification. A summary of published standards on verticality requirements is presented in Table 1. A recently developed method of evaluating verticality is the Shaft Area Profile Evaluator. This wireless device can be lowered at up to 300 mm/sec into a bored pile or diaphragm wall excavation to determine the element verticality, shape, and excavation volume. A photo of the device being lowered into a bored pile excavation is presented in Figure 1. The major components of the device 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 through the drilling fluid at each test depth by measuring the travel time across the known calibration distance. The travel time through the drilling fluid to the excavation sidewall and back is then measured by the ultrasonic transmitters and receivers. This measured time, along with the associated measured 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.

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

Specification or Code	Verticality
US FHWA Guide Specification, Brown et. al., (2018)	• 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)

Figure 1. Shaft Area Profile Evaluator being lowered into a bored pile excavation.

A screen display of the ultrasonic signals is presented in Figure 2. Each row displays the signal from each ultrasonic receiver with the corresponding sensor identification number. Sensor 1 was pointed north at the beginning of the test. The bottom row displays the calibration pulse at the test depth. From the displayed calibration signal, the wave speed through the drilling fluid 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 righthand side, an X-Y plot of the bored pile radius from its starting centroid identified by the dashed plus sign is displayed. It is apparent that the centroid of the bored pile at this depth is east and slightly north from its starting coordinates.

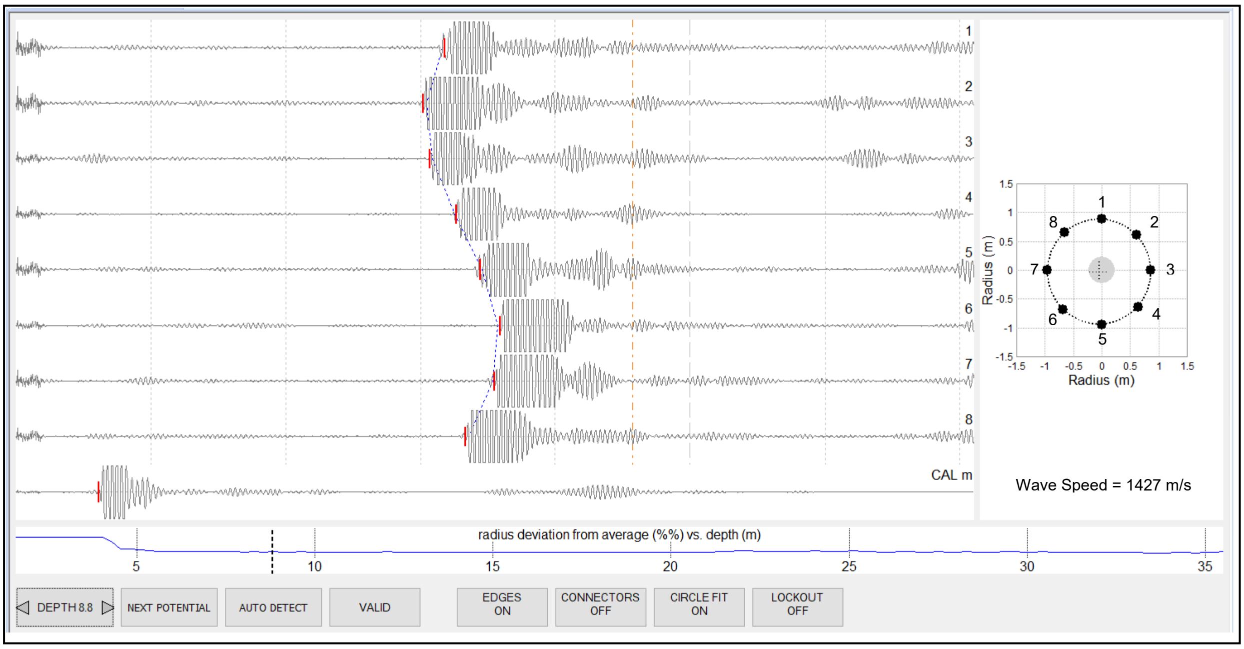


Figure 2. Ultrasonic signals at a test depth.

Figure 3 presents Profiles 5-1, 6-2, 7-3, and 8-4 through a different bored pile. In this example, the base of the bored pile is clearly drifting towards the northwest. The calculated eccentricity in Profiles 5-1, 7-3, and 8-4 ranged from 0.18 to 0.27 m. Figure 4 presents the maximum calculated eccentricity in the pile and the resulting verticality of 2.91%. This calculated verticality exceeds the magnitude allowed in any of the specifications listed in Table 1.

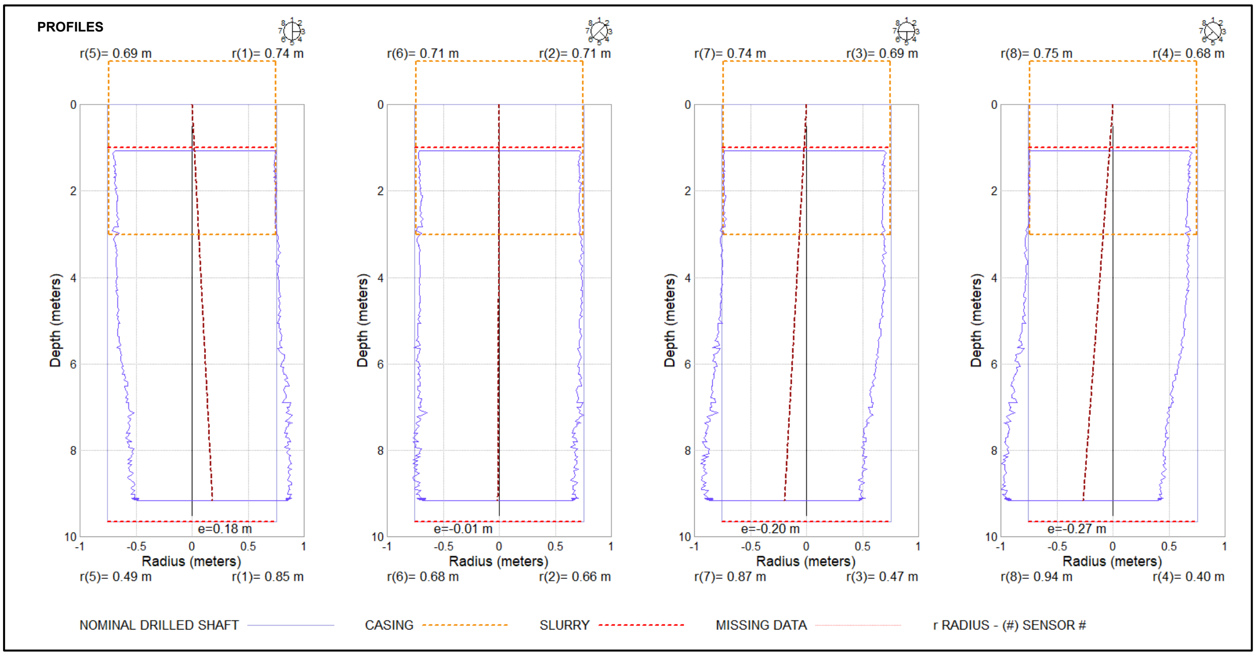


Figure 3. N-S, NE-SW, E-W, and SE-NW profiles of radius vs depth through bored pile.

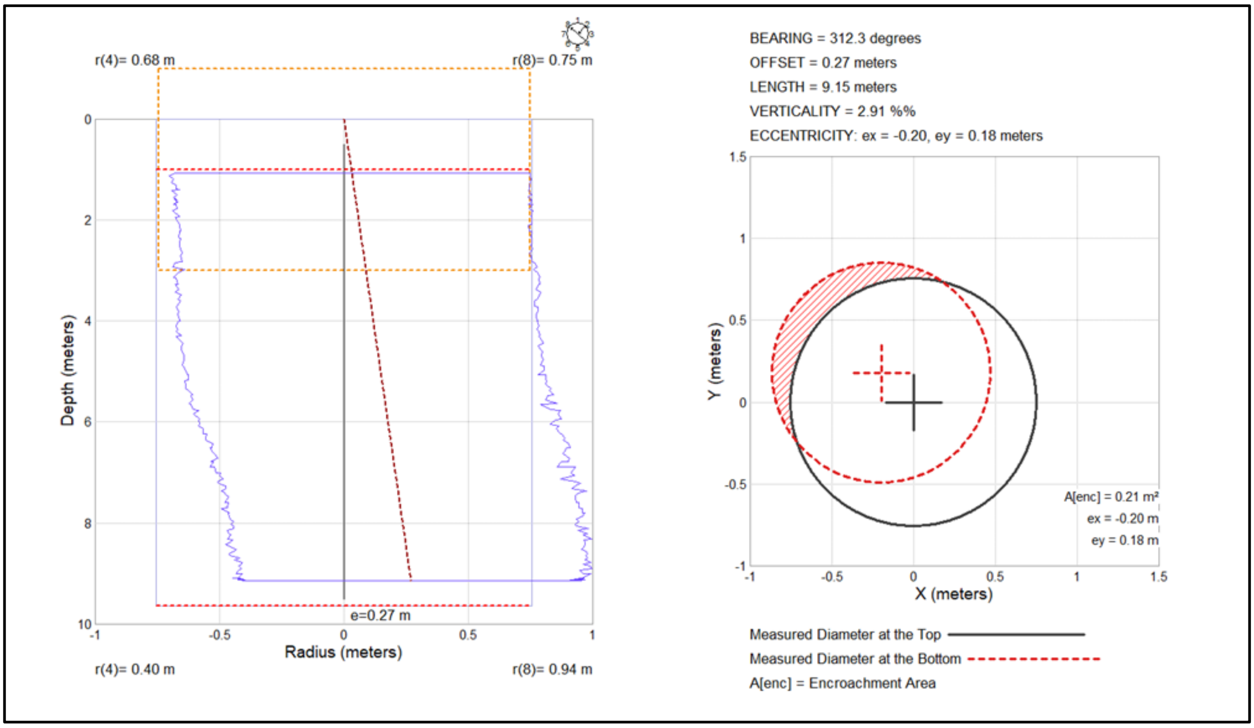


Figure 4. Maximum calculated eccentricity and resulting bored pile verticality.

3. Base Cleanliness Evaluation

The required base cleanliness of bored piles prior to concrete placement depends on the foundation support mechanism, local practice and project specifications. A summary of some published standards on base cleanliness requirements is presented in Table 2.

Table 2. Summary of Base Cleanliness Requirements for Bored Piles

Specification or Code	Base Cleanliness
US FHWA Guide Specification Brown et. al., (2018)	• 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 of 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
Canadian Foundation Engineering Manual, 4th Edition (2006)	• Regardless of the procedure used for excavation, it is essential that the base be cleaned to the sound founding material.

A recent method of evaluating base cleanliness is the Shaft QUantitative Inspection Device. This device uses three 10 cm^2 force penetrometers and three 521 mm diameter debris plates to assess base cleanliness. The force penetrometers can be equipped with either flat tips for debris thickness assessments or 60-degree cone tips for evaluation of the bearing material. A photograph of the device with flat tip penetrometers is shown in Figure 5. The penetrometers are pushed into the base material using the weight of the drill rig's Kelly bar. The penetrometers can be pushed to a maximum penetrometer pressure of 100 MPa.

Figure 5. Shaft Quantitative Inspection Device.

Data analysis includes two penetration resistance thresholds, one associated with the penetration resistance defining debris, DTH, and the second one defining the penetration resistance offered by natural soils, PTH. Each penetrations 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 difference in measured displacement between crossing the DTH and PTH thresholds is the defined debris thickness.

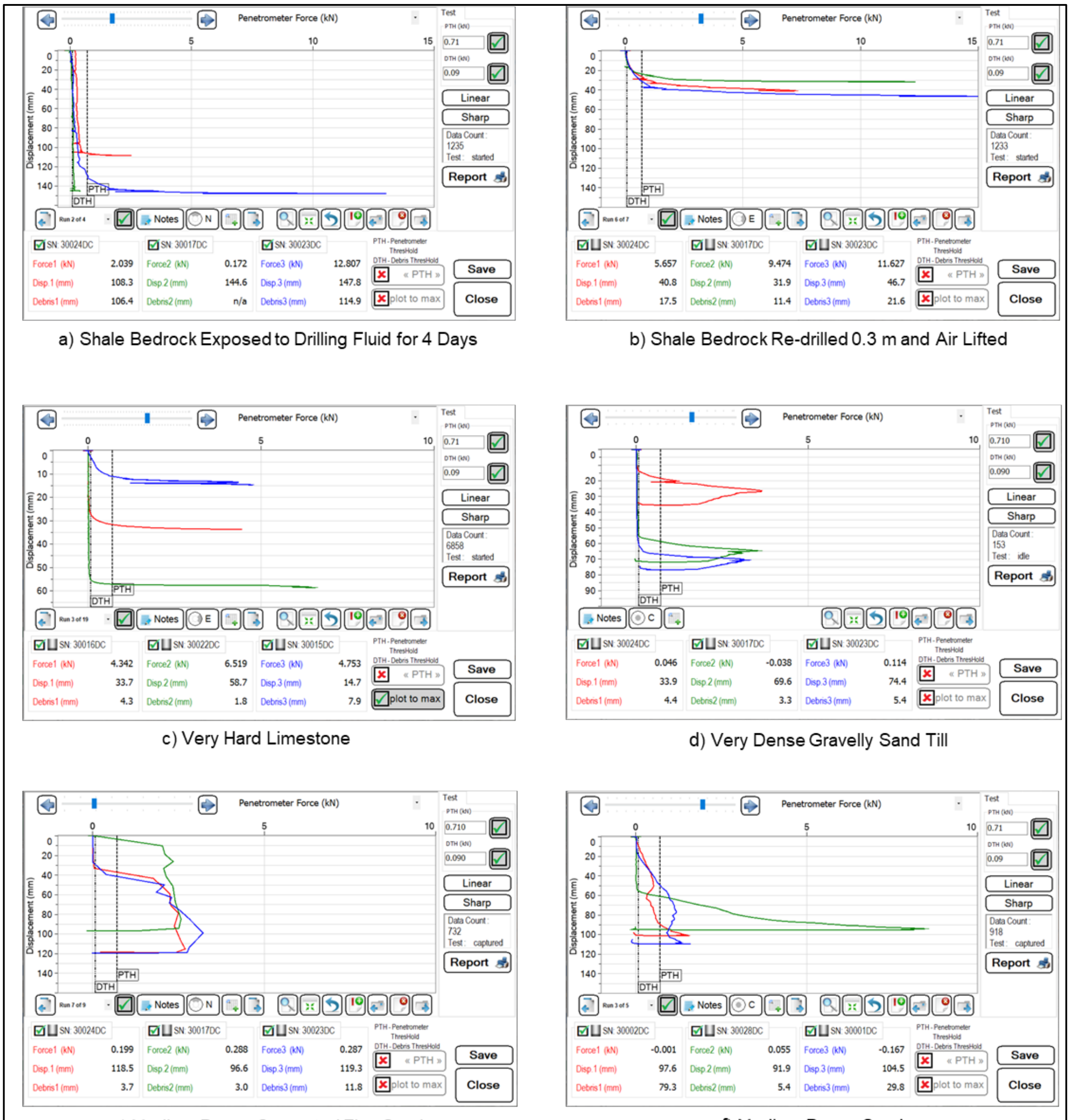
Base cleanliness test results from several tests in different materials are shown in Figure 6. In Figure 6a, penetrometer force-displacement results are shown for a test in a bored pile bearing in shale bedrock. The pile excavation had been left open and filled with drilling fluid for 4 days prior to the testing. Due to degradation of the bedrock over time, from 106.4 mm to in excess of 114.9 mm of a displacement occurs between crossing the DTH and PTH thresholds. The shaft was subsequently drilled 0.3 m deeper, the base cleaned with an airlift, and a re-test immediately performed. The re-test results, shown in Figure 6b, indicated from 11.4 to 21.6 mm of debris which was within specification limits.

Penetrometer force-displacement results for a pile bearing on a hard limestone are presented in Figure 6c. Note that the displacements between the DTH and PTH thresholds range from 1.8 to 7.9 mm indicating a very clean bearing surface. The individual penetrometer force-displacement plots also become nearly horizontal at displacements of approximately 13, 33, and 57 mm indicative of a very hard limestone but slightly uneven bearing layer.

In Figure 6d, penetrometer force-displacement results are shown for a test in a bored pile bearing in a very dense gravelly sand till with a Standard Penetration Test (SPT) N value of 100 blows / 30 mm. The individual penetrometer force-displacement plots cross the DTH threshold at displacements of 14.0, 55.4, and 61.4 mm and the PTH threshold at 18.4, 58.7, and 66.9 mm, respectively. This indicates a very clean bearing surface with the debris thickness ranging from 3.3 to 5.4 mm. Note that the bearing layer is a sandy glacial till layer instead of bedrock, so all of the penetrometer force-displacement results substantially displace after reaching the peak penetrometer force.

Figure 6e presents penetrometer force-displacement results for a bored pile terminated on a medium dense cemented fine sand with a SPT N value of 12. The bored pile base was cleaned with a flat bottom cleanout bucket prior to base cleanliness testing. Test results indicate a very clean base condition with 3.0 to 11.8 mm of debris. The penetrometer force-displacement plots plunge at a penetrometer force of approximately 2 kN in the cemented sand material.

Penetrometer force-displacement results for a bored pile bearing on a medium dense coastal plain sand are presented in Figure 6f. In this case, one penetrometer indicates a very clean base with only 5.2 mm of debris, one penetrometer indicates 28.4 mm of debris which is close to most specification limits, and the third penetrometer indicates 78.2 mm of debris which exceeds most specification limits. The average of the three debris values is 37.2 mm which would necessitate additional cleaning by most specifications.



a) Shale Bedrock Exposed to Drilling Fluid for 4 Days

PTH (kN) 0.71; DTH (kN) 0.09; Data Count : 1235; Test : started

SN 30024DC		SN 30017DC		SN 30023DC	
Force1 (kN)	2.039	Force2 (kN)	0.172	Force3 (kN)	12.807
Disp 1 (mm)	108.3	Disp 2 (mm)	144.6	Disp 3 (mm)	147.8
Debris1 (mm)	106.4	Debris2 (mm)	n/a	Debris3 (mm)	114.9

b) Shale Bedrock Re-drilled 0.3 m and Air Lifted

PTH (kN) 0.71; DTH (kN) 0.09; Data Count : 1233; Test : started

SN 30024DC		SN 30017DC		SN 30023DC	
Force1 (kN)	5.657	Force2 (kN)	9.474	Force3 (kN)	11.627
Disp 1 (mm)	40.8	Disp 2 (mm)	31.9	Disp 3 (mm)	46.7
Debris1 (mm)	17.5	Debris2 (mm)	11.4	Debris3 (mm)	21.6

c) Very Hard Limestone

PTH (kN) 0.71; DTH (kN) 0.09; Data Count : 6858; Test : started

SN 30016DC		SN 30022DC		SN 30015DC	
Force1 (kN)	4.342	Force2 (kN)	6.519	Force3 (kN)	4.753
Disp 1 (mm)	33.7	Disp 2 (mm)	58.7	Disp 3 (mm)	14.7
Debris1 (mm)	4.3	Debris2 (mm)	1.8	Debris3 (mm)	7.9

d) Very Dense Gravelly Sand Till

PTH (kN) 0.710; DTH (kN) 0.090; Data Count : 153; Test : idle

SN 30024DC		SN 30017DC		SN 30023DC	
Force1 (kN)	0.046	Force2 (kN)	-0.038	Force3 (kN)	0.114
Disp 1 (mm)	33.9	Disp 2 (mm)	69.6	Disp 3 (mm)	74.4
Debris1 (mm)	4.4	Debris2 (mm)	3.3	Debris3 (mm)	5.4

e) Medium Dense Cemented Fine Sand

PTH (kN) 0.710; DTH (kN) 0.090; Data Count : 732; Test : captured

SN 30024DC		SN 30017DC		SN 30023DC	
Force1 (kN)	0.199	Force2 (kN)	0.288	Force3 (kN)	0.287
Disp 1 (mm)	118.5	Disp 2 (mm)	96.6	Disp 3 (mm)	119.3
Debris1 (mm)	3.7	Debris2 (mm)	3.0	Debris3 (mm)	11.8

f) Medium Dense Sand

PTH (kN) 0.71; DTH (kN) 0.09; Data Count : 918; Test : captured

SN 30002DC		SN 30028DC		SN 30001DC	
Force1 (kN)	-0.001	Force2 (kN)	0.055	Force3 (kN)	-0.167
Disp 1 (mm)	97.6	Disp 2 (mm)	91.9	Disp 3 (mm)	104.5
Debris1 (mm)	79.3	Debris2 (mm)	5.4	Debris3 (mm)	29.8

Figure 6. Base Cleanliness Tests in Various Materials of Penetrometer Resistance vs Displacement.

4. Concrete Integrity and Cover

The quality and integrity of bored pile and diaphragm wall concrete is extremely important to satisfying the foundation performance requirements. Figure 7, from Piscsalko et al (2016), illustrates the effect of average radius reduction on the bored pile bending capacity (moment), geotechnical capacity (side shear), and structural capacity (area). An average radius reduction greater than 6% may be unacceptable depending on its location within the pile. Maintaining the required concrete cover is also essential for durability considerations. Minimum reduction in average concrete cover requirements are presented in Table 3.

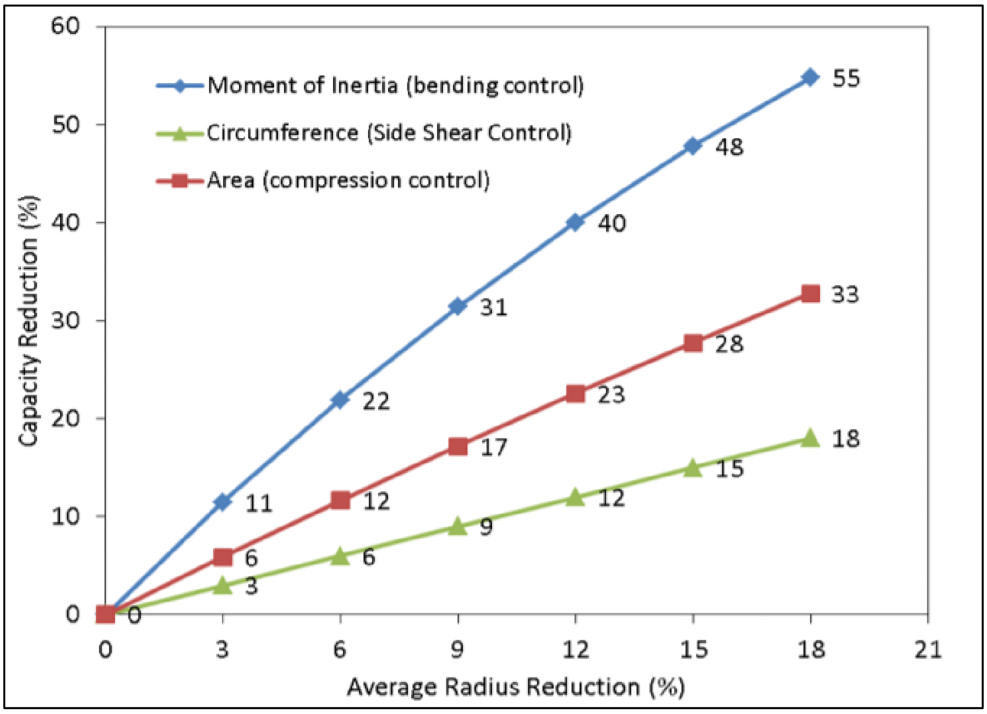


Figure 7. Effect of average radius reduction on bored pile capacity from Piscsalko et al., (2016).

Table 3. Summary of Concrete Cover Requirements for Bored Piles

Specification or Code	Minimum Cover
US FHWA Guide Specification, Brown, et. al., (2018)	• 76 mm for pile diameter ≤ 0.91 m • 102 mm for pile diameter > 0.91 m and ≤ 1.52 m • 152 mm for pile diameter > 1.52 m

The only test method that can evaluate both the concrete integrity and concrete cover is Thermal Integrity Profiling. This newer method uses Thermal Wire cables attached to the reinforcing cage. For bored piles, these wires are located at 300 mm spacings around the interior of the reinforcing cage. For diaphragm walls, the cables are typically attached to the reinforcing cage at opposite locations along the length of the rectangular panel. Each individual thermal wire cable has thermal sensors spaced 300 mm apart along the length of the cable.

In a typical application, the Thermal Wire cables run the full length of the reinforcing cage. 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 temperature of each thermal sensor is read by the data loggers, typically every 15 minutes, and the temperature readings are pushed to the Cloud for real time analysis. Figure 8 shows the Thermal Wire cables being attached to the inside of a 2083 mm diameter reinforcing cage (left), and the TAG and TAP-Edge units on a 914 mm reinforcing cage post installation (right).

As the concrete cures, heat is generated by the hydrating cement which increases the temperature within a bored pile or diaphragm wall. 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.

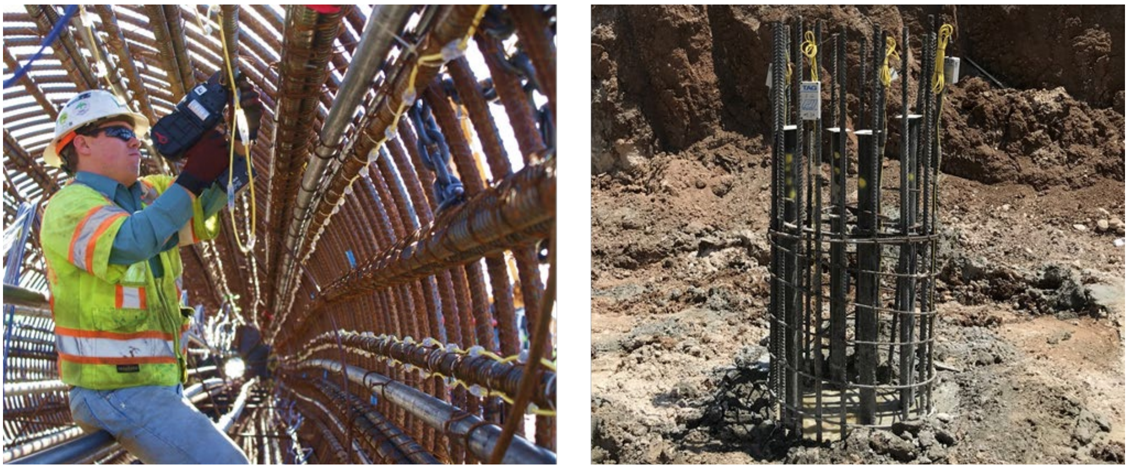


Figure 8. Thermal Wire cable attachment (left) and TAG and TAP-Edge Equipment (right).

The overall, average temperature of all Thermal Wire readings of a given foundation element over the embedded depths can be directly related to the overall volume of concrete installed. For bored piles, the pile 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 pile 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.

Figure 9 presents Thermal Integrity Profiling results for a 1524 mm diameter bored pile. 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 modelled and test results adjusted for their effects as described in 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 below the 6% reduction criteria, warranting further evaluation. Concrete core holes encountered a 150 mm thick void at this location necessitating pile remediation. A 3D representation of the pile and cage overlain on the soil description is presented in the rightmost plot.

For diaphragm walls, the temperature versus depth information can be reviewed and assessed based on wire locations. Due to the influence of the surrounding soil or concrete, corner wire locations will have cooler temperature profiles versus depth than wires located away from the corner along a given panel face. Wires located at the same position on opposite panel faces can be used to assess bulging, inclusions, and cage shifting similar to the temperature response noted above for cylindrical bored piles versus depth.

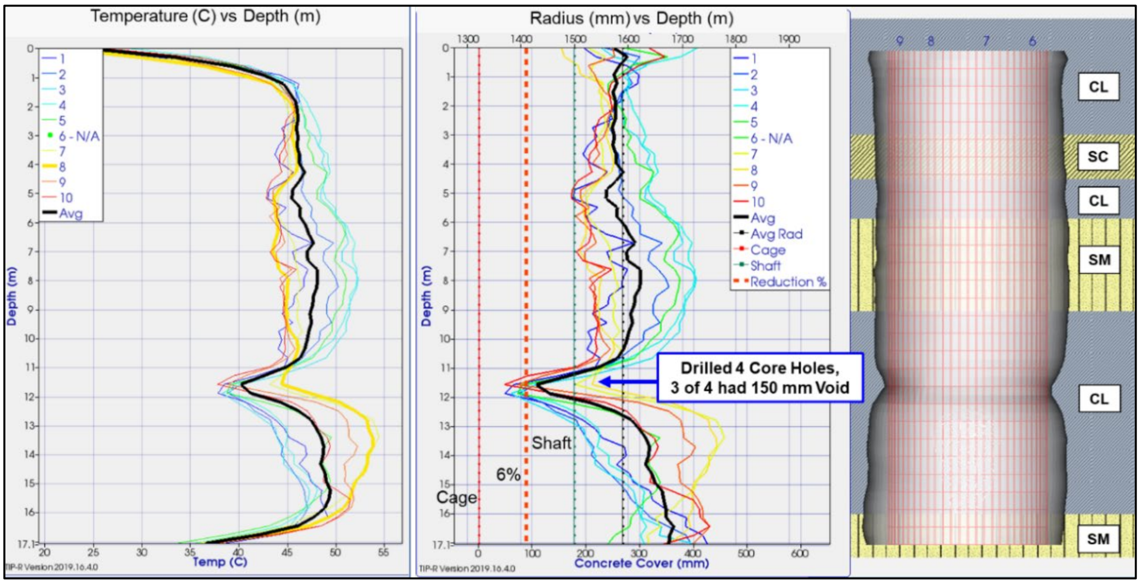


Figure 9. Thermal Integrity Profiling results on a bored pile.

Figure 10 presents Thermal Integrity Profiling results for a 1.2 m by 7 m diaphragm wall panel with 12 Thermal Wire cables. Cable locations are shown on the panel diagram. The left plot presents the measured temperatures versus depth for all 12 of the Thermal Wire cables at the time of peak temperature. Note that the panel has a relatively uniform temperature versus depth for most wires with the exception of Wires 1 and 12. These two wires show a significant 10 degree C drop in temperature between 8.5 and 10.5 m. Local reductions are also noted in these same wires from 1 to 5 m and from 13.7 to 15.2 m. Wires 4 and 5 also exhibit a local reduction near the 2 to 4 m depth. The integrity issues near 9.5 and 14.5 m correspond to depths where tremie pipe sections were removed.

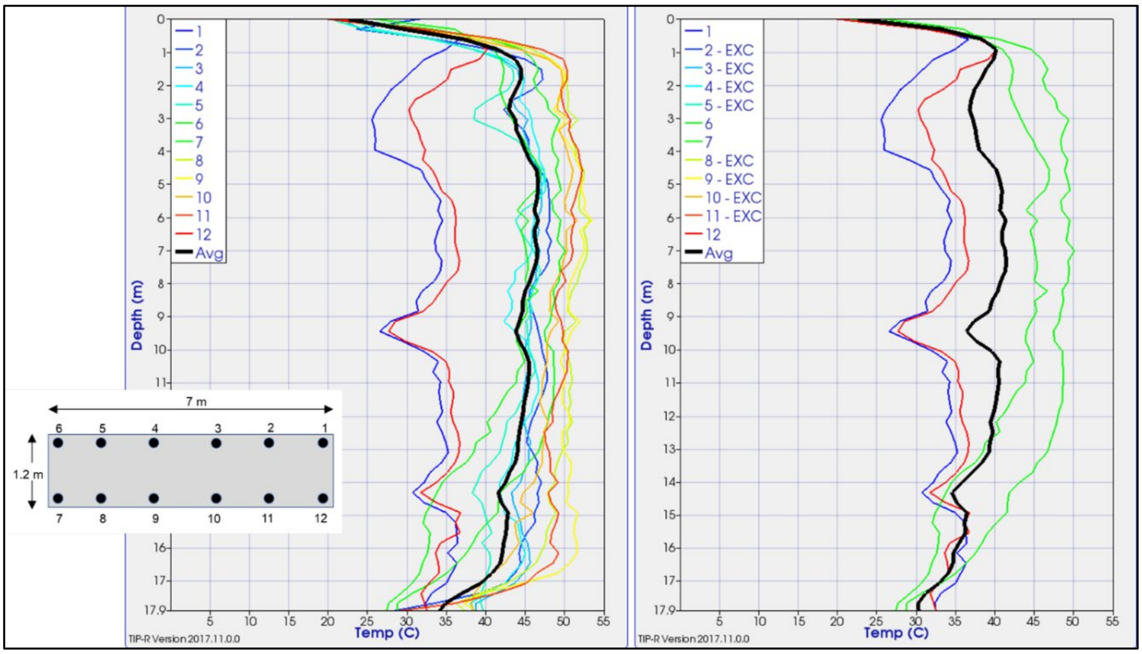


Figure 10. Thermal Integrity Profiling results on a diaphragm wall panel.

Lower quality or contaminated concrete is also indicated by Wires 5, 6 and 7 between the depths of 10 m to the panel base by their gradually cooling and more linear behaviour than the expected hyperbolic roll off in temperature near the base. The right plot presents temperature data versus depth for only the four wires at the panel corners. Wires 1 and 12 are notably cooler while the opposite wires, Wires 6 and 7 are warmer. This indicates the reinforcing cage is shifted toward Wires 1 and 12. Hence, the areas with the most significant integrity concerns include the panel interfaces with adjacent panels.

5. Conclusions

This paper presented test results from several newer quality control and quality assurance technologies that can be used for bored pile and diaphragm wall construction. Devices are available that can quickly assess the as-built shape, vertical alignment, base cleanliness, cage alignment, concrete cover, and concrete integrity on deep foundation elements cast with tremie concrete under drilling slurry. Recent international specification requirements for quality assurance tests of deep foundation element verticality, base cleanliness, and concrete cover were also reviewed.

The loads supported by deep foundation elements continue to increase as a result of improved design practices and construction confidence from quality control tests. Confirmation that the as-built shape, verticality, base cleanliness, cage alignment, concrete cover, and concrete integrity of a deep foundation element are in compliance with construction specifications is essential for satisfying deep foundation performance requirements and long-term durability. Examples were presented of a bored pile verticality test that exceeded verticality requirements, bored pile base cleanliness tests in a variety of soil and rock materials, as well as concrete integrity results for a bored pile with a tremie breach and a diaphragm wall panel with substantial concrete integrity concerns and cage shifting at the panel interface.

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