Integrity testing of concrete deep foundation with focus on thermal methods

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ABSTRACT
Integrity test methods for concrete deep foundations are reviewed. The most common and traditional non-destructive evaluation or quality assurance for concrete foundations have been methods involving Cross-hole Sonic Logging (CSL) or its variant, Single-hole Sonic Logging (SSL), Gamma-gamma Logging (GGL), Sonic Echo (SE), and Impulse Response (IR). The latter two are generally known as Pile Integrity Testing (PIT) method. These conventional tests are generally carried out several days after completion of pile installation. In the last several years, a new quality assurance method for cast in place concrete deep foundations has been developed. It is based on concrete thermal behavior (concrete hydration) to assess the integrity of installed concrete deep foundations. This latest method is known as Thermal Integrity Profiling (TIP) and is covered in ASTM D 7949: Standard Test Methods for Thermal Integrity Profiling of Concrete Deep Foundations. Despite being a very recent development, TIP has been gaining widespread acceptance as a quick quality assurance method for concrete deep foundations. TIP test results can be available as early as 24 hours after concrete placement. Traditional and TIP methods are discussed with respect to their relative advantages and limitations. Current trends and status of TIP method in the USA, specifically with respect to state Departments of Transportation (DOTs) is reviewed. Finally, two case studies involving TIP testing are presented showing the effectiveness of the method in providing quality assurance at a very early stage and hence contributing to a timely completion of pile installation and subsequently to timely project completion.

RÉSUMÉ
Les méthodes de test d'intégrité pour fondations profondes en béton sont passées en revue. Les méthodes les plus courantes et les plus traditionnelles d’évaluation non destructive ou d’assurance qualité des fondations en béton sont les méthodes de journalisation sonique à trous croisés (CSL) ou sa variante, la journalisation sonique à un trou (SSL), la journalisation gamma-gamma (GGL), l’écho sonique. (SE) et réponse impulsionnelle (IR). Les deux derniers sont généralement connus sous le nom de méthode de test d’intégrité de pile (PIT). Ces tests classiques sont généralement effectués plusieurs jours après la fin de l'installation des pieux. Ces dernières années, une nouvelle méthode d’assurance qualité pour les fondations profondes en béton coulé sur place a été mise au point. Il est basé sur le comportement thermique du béton (hydratation du béton) afin d'évaluer l'intégrité des fondations profondes en béton installées. Cette dernière méthode est connue sous le nom de profil d’intégrité thermique (TIP) et est décrite dans la norme ASTM D 7949: Méthodes d’essai standard pour le profilage de l’intégrité thermique de fondations profondes en béton. Bien qu’il s’agisse d’un développement très récent, TIP est de plus en plus reconnu comme une méthode d’assurance qualité rapide pour les fondations profondes en béton. Les résultats du test TIP peuvent être disponibles dès 24 heures après la mise en place du béton. Les méthodes traditionnelles et TIP sont discutées en fonction de leurs avantages et limites relatifs. Les tendances et l’état de la méthode TIP aux États-Unis, en particulier en ce qui concerne les États DOT, sont passés en revue. Enfin, deux études de cas impliquant des tests TIP sont présentées, montrant l'efficacité de la méthode pour fournir une assurance qualité à un stade très précoce, contribuant ainsi à l'achèvement en temps voulu de l'installation des pieux et ensuite à l'achèvement du projet.

1 INTRODUTION

Integrity testing is a non-destructive evaluation method used to assess the quality of cast-in-place concrete deep foundations. These methods compare the homogeneity or uniformity of the tested foundation element. In general, integrity tests are meant to detect zones of defect (i.e., anomaly) either due to reduced cross-section or due to inferior quality material. Integrity test methods may involve techniques based on acoustic echo, ultrasonic cross hole, gamma-gamma, or thermal logging procedures.

Integrity tests are generally used for quality assurance of newly constructed concrete deep foundations; they can also be used to evaluate the condition of existing foundations (Rausche 2004). This article reviews only those methods used for the quality assurance of newly constructed concrete deep foundations. While integrity testing can be used for both cast-in-place and driven piles, this article considers the former only.

1.1 Integrity testing versus pile load testing

As opposed to most pile load tests, integrity tests are non-destructive by nature and will not result in a change in load carrying capacity of the element tested. Integrity tests do not measure load carrying capacity of tested foundation elements but indicate the existence of defects, etc. In general, pile load tests measure the ultimate load carrying capacity; integrity tests yield results that are general indicators of performance but do not provide quantitative measure of performance.

2 COMMON INTEGRITY TEST METHODS

As indicated above, integrity tests may be conducted for quality assurance of new constructions or for the evaluation of existing deep foundation elements. Some of the common methods for the former application are briefly described herein:

- Pile integrity testing (PIT)
    - Sonic echo (SE)
    - Impulse response (IR)
- Cross hole sonic logging (CSL)
- Gamma-gamma logging (GGL)
- Thermal integrity profiling (TIP)

2.1 Sonic Echo (SE)

Sonic echo is also known as low strain impact integrity testing (ASTM D5882) and probably one of the initial integrity test methods developed for quality assurance (QA) of deep concrete foundations. It is based on wave propagation theory. The method involves striking the head of the pile with a small (usually plastic) hammer that sends an acoustic wave down the pile. A geophone or accelerometer placed at the pile top measures the reflected waves. Typically, the wave is reflected after reaching the pile toe or encountering a defect. Iterative signal matching technique is carried out to obtain the pile profile.

Sonic echo is quick and inexpensive; however, the analysis and interpretation are not always conclusive.

2.2 Impact Response (IR)

Impact response is similar to sonic echo except that it utilizes more instrumentation and more sophisticated analysis that incorporates Fast Fourier Transform (FFT) analysis. As a result, both SE and IR are usually used together (SEIR) to better assess pile integrity.

2.3 Cross hole sonic logging (CSL)

CSL involves installing access tubes or ducts (typically 50 mm in diameter) in the pile or shaft during construction. The tubes need to be stiff enough and are commonly made from steel or PVC, steel being preferred to prevent debonding of concrete resulting in a false anomaly. The access ducts are generally affixed to the interior of the reinforcement cage. The number of access ducts depends on the size of foundation element, minimum is typically 4 ducts. For small shafts (less than 1 m diameter), one access duct at the centre will suffice (see below for single sonic logging). CSL is one of the more commonly specified deep foundation QA methods by most state departments of transportation in the USA.

CSL measures the travel time and relative energy of an ultrasonic pulse between parallel access ducts (cross hole) or in a single tube (single hole) installed in the deep foundation element. This method is most applicable when performed in tubes that are installed during construction. After concrete hardens, two ultrasonic transducers (one emitter and one receiver) are simultaneously lowered into a set of parallel ducts. By plotting the elapsed time between the emitted and received signals with depth, the quality of concrete between the ducts can be assessed. Typically, the First Arrival Time (FAT) and Relative Energy (RE) of pulses intercepted by the receiver are measured and plotted (Amir 2019).

For smaller shafts (less than 1 m in diameter), single hole sonic logging (SSL) with a single duct at the centre of the shaft is used. For single hole tests the access tubes must be plastic (typically PVC) tubes. Testing should therefore be performed as soon as practicable in order to avoid debonding issues (ASTM D6760). Both transducers (emitter and receiver) are inserted in the single duct during measurement. The transducers are typically 600 mm apart.

2.4 Gamma-gamma logging (GGL)

Gamma-gamma logging is conducted in an access tube, similar to CSL described above. Instead of a probe with ultrasonic source, one with a weak radioactive source (Cesium-137) is used. The access tube is typically a nominal 50 mm diameter PVC pipe which is attached to the reinforcing cage. The source emits gamma radiation similar to a nuclear density gauge and a gamma-gamma detector such as Geiger-Mueller counter is used. Similar to a nuclear density gauge, the source emits gamma radiation in all directions. Photons are partly absorbed by the surrounding concrete and partly backscattered depending on the density of the surrounding material (Amir 2019). Higher backscatter (photon count) shows low concrete density. Hence, the quality of concrete surrounding the reinforcement cage can be inferred. The detection radius is typically limited to 75 to 100 mm.

GGL seems to be rarely used compared to other integrity test methods. It requires interpretation by experience personnel. It is also subject to regulatory restrictions due to the special requirement in handling, storing and transport of radioactive materials (e.g., refer to California Test 233, Caltrans 2005).

2.5 Thermal integrity profiling (TIP)

Thermal integrity profiling involves the use of thermal sensors that measure the hydration temperature of concrete to evaluate the quality of cast-in-place concrete deep foundations. Thermal profiles obtained by measuring the hydration temperature of cast-in-place deep foundation elements will help to evaluate the homogeneity of concrete and regularity of the cross-section. TIP testing is conducted in accordance with ASTM D7949. There are two methods of carrying out TIP testing: Method A – infrared thermal probes lowered into access tubes (ducts) installed in foundation elements during construction; and Method B – strings of thermal sensors (thermistors) affixed to reinforcing cage installed in deep foundation element during construction. TIP testing is now specified in numerous state Departments of Transportation (DOTs) as an alternative QA method for cast-in-place concrete foundations.

The TIP method has a measurement accuracy of 1 °C or better. For brevity, methods A and B are referred to as the probe method and the wire method, respectively. Thermal integrity profiling was initially developed by professor Gary Mullins of the University of South Florida (Mullins and Kranc 2004). Collaboration between Foundation and Geotechnical Engineering, LLC (FGE) and Pile Dynamics, Inc. (PDI) resulted in further implementation of the method (Likins and Mullins 2011). In the probe method, access ducts are attached to the reinforcing cage of the deep foundation element during construction. The access ducts are generally spaced uniformly throughout the foundation cross-section, and equidistant from the centre.

During hydration, concrete temperature is highest at the centre of foundation unit (shaft) and lowest at the shaft/soil interface. At the cage location, the thermal gradient of hydration temperature is linear with respect to the radial distance from the shaft centre. For a shaft with homogenously placed concrete and concentric cage, the temperature at a given depth should be the same for all sensor locations around the cage. A location with a lower temperature than average indicates a possible defect (poor quality or necking) or a location close to the soil pile interface. A warmer temperature may indicate a bulge or a location closer to the shaft centre. Since concrete temperature and shaft size can be directly related, it is possible to evaluate the cross-sectional properties by measuring the hydration temperature.

The field procedure for thermal integrity profiling involves installing access tubes (probe method) or embedded strings of thermal sensors during construction. For cylindrical cross-sections, one access tube or thermal wire string is installed for every 300 mm of diameter. For shafts with 1 m diameter or greater, a minimum of 4 access tubes or thermal wire strings will be required. For small diameter cast-in-drilled-hole piles (less than 1 m in diameter), one access tube or thermal wire string is installed at the centre of the foundation unit.

Figure 1 shows a typical arrangement of thermal sensors (or access tubes) used for thermal integrity profiling. The four tubes or sensor strings are arranged approximately 90 degrees from each other.

For the probe method, temperature measurement will commence after peak hydration is thought to have been reached. This might take up to 48 to 72 hours depending concrete size and composition. The infrared thermal probe along with a depth encoder are lowered steadily into each access tube, typically at a rate 150 mm/s. Temperature measurements will be taken at prescribed depth intervals, approximately every 300 mm. This will be repeated for all access ducts.

For the wire method, a datalogger is connected to each thermal sensor string immediately after concrete is poured. It is possible to regularly interrogate the datalogger (while still recording temperature data) to assess if peak hydration temperature has been reached. Once peak temperature is reached, the datalogger can be disconnected and data downloaded. Optionally, data can also be uploaded to the cloud-based server where it can be easily accessed.

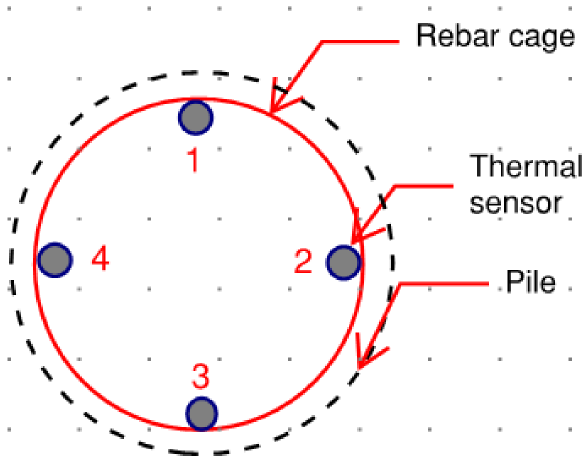


Figure 1. Typical arrangement of thermal sensors in a 4-sensor TIP test setup. Note: the schematic applies for both probe and wire methods; access tubes or strings of thermal probes are attached to reinforcement cages.

TIP testing will also indicate shifting (eccentricity) of the reinforcing cage. This can be accomplished by comparing the thermal profile from the thermal sensors installed 180 degrees from each other. Consider thermal sensors 2 and 4 in Figure 1 above. Assume that the cage shifts such that location 2 is closer to the shaft/soil interface and location 4 moves inward closer to the centre of the shaft. In this situation, sensors along string #2 will consistently show cooler temperatures than average; likewise, sensors along string #4 will show warmer temperature (refer to Figure 2 below).

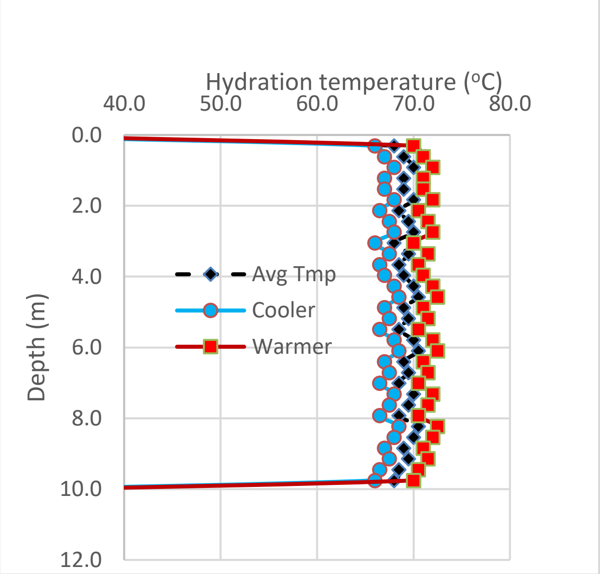


Figure 2. Hypothetical thermal profile with cooler and warmer thermal strings indicating shift in reinforcement cage

3 COMPARISON OF INTEGRITY TEST METHODS

Table 1 summarizes the relative advantages and disadvantages of the integrity tests presented herein. As shown in Table 1, most of the methods presented have significant limitations. The thermal method, despite being the most recent of all, seems to boast the most advantages and fewest limitations. One of the main limitations of the thermal method is that it can only be performed during concrete hydration (especially the wire method). However, due to the relative reliability of the method, the method will rarely require repeating the test.

Table 1. Comparison of integrity tests

Method	Advantages	Limitations
SE	- Relatively simple - Inexpensive to conduct	- Interpretation generally difficult - Minor defects not detectable - Limited length - No detection below a defect - Cannot detect side /quadrant
IR	- Similar to SE; force applied to pile vs. time can be measured - Better analysis	- Same general limitations as SE; slightly easier interpretation
CSL/ SSL	- No depth limitation - Detects defect quadrant/ side - 3D tomography available	- Wait time up to 1 week - Needs access tube - Cannot evaluate concrete cover - Debonding causes false anomaly
GGL	- Can evaluate concrete cover - Complements CSL	- PVC access tube required - Probe size issue - Radioactive (Cs-137)
TIP	- Detects defect depth and quadrant - Early detection of defect - Detects cage eccentricity - Detects cover thickness - No debonding issue	- Can test during hydration only - Sacrificial wires (wire method) - Drilled or auger cast piles only

4 COMPARISON OF PROBE AND WIRE METHODS

Both methods of thermal integrity profiling (TIP) are described in ASTM D7949. TIP was initially developed based on the probe method. Subsequent development of the wire method seems to have sped up the relative acceptance of TIP testing in the piling community recently (especially the wire method). Table 2 provides a summary comparison of the both methods of thermal integrity profiling. Both methods are generally comparable; however, the wire method is much more versatile and is less labour intensive in the field.

Table 2. Comparison of the probe and wire methods

Method	Advantages	Limitations
Probe method	- Can be used in CSL tubes - Probe can be reused	- Tubes require dewatering - Labour intensive field data collection - High cost (for steel tubes) - May need to repeat test - Difficulty in picking peak temperature time
Wire method	- Wires easier to install - Wires less expensive - Continuous data recording (datalogging) - Can easily detect peak temperature - Early detection of defects	- Sacrificial thermal sensors - Wire survivability concerns - Test cannot be repeated

5 CASE STUDY OF TIP TESTS

Results of two TIP test examples are presented to show the use of TIP testing in quickly providing quality assurance of cast-in-place deep foundation elements. Both TIP tests were based on the wire method (Method B of ASTM D7949). The first TIP test example is for quality assurance (QA) of cast-in-drilled-hole (CIDH) concrete pile foundation installation. The second TIP test example is for the evaluation of ground improvement using the method of Rigid Inclusions (RI).

Details of the first TIP example are summarized in Table 3 below. Please note that the placed concrete volume is approximately 6% greater than the nominal volume calculated from the design dimension. This is to account for any inconsistencies (including difference in ground response, pumping rate, etc.).

Installation of the CIDH pile involved auger drilling & cleaning the hole, pouring concrete at the bottom of the auger while retrieving the auger, and installing the reinforcing cage. The reinforcing cage has a centre bar to which a single string of thermal wire was attached. The thermal wire string had sensors spaced every 0.3 m along the shaft. Once the rebar cage was installed, the datalogger was immediately connected to the string of thermal sensors to continuously record the hydration temperature. The datalogger was set to sample temperature readings every 15 minutes. After confirming that peak hydration temperature was reached, the datalogger was disconnected from the thermal sensor string and the temperature data downloaded for further analysis and interpretation. For this example, peak hydration temperature was reached approximately 20.5 hours after the concrete was cast. In general, time for peak temperature will depend on the size of the foundation element and the concrete mix design.

One key component of thermal integrity profiling is the record of concrete volume placed. Any additional detail on pile installation will help improve the quality of thermal data analysis and interpretation. If the concrete volume is recorded correctly, the overall average temperature readings of the thermal strings can be directly related to the concrete volume and subsequently, to the effective radius (diameter) of the foundation element (in this case cylindrical).

Except near the top and bottom of the foundation element, the temperature distribution along the shaft or any deep foundation element is anticipated to be reasonably uniform. A major lack of uniformity is either due to defect or a significant heterogeneity of the surrounding soil condition. The top and bottom of the shaft have different boundary conditions compared to the remainder of the shaft due to temperature dissipation at these locations, which also involves heat loss to the air (at the top) and to the soil (at the toe), in addition to the radial heat loss to the surrounding soil. The different thermal boundary condition at the top and bottom is referred to as the roll-off effect and needs to be corrected during data analysis. The top and bottom correction is applied using hyperbolic tangent curves. Figure 3 shows the TIP test results for example 1.

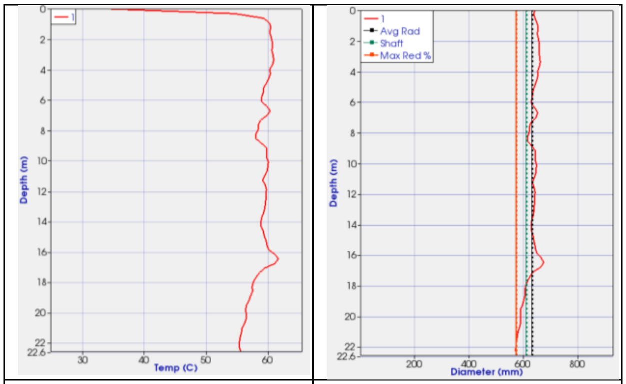
Table 3. Details of pile for TIP test example 1

Length (m)	Diameter (m)	Centre bar dia. (mm)	Concrete volume (m^3)	
			Nominal[1]	Placed[2]
22.6	0.6	44	6.66	7.05

[1]volume calculated based on pile design length and diameter

[2]volume includes approximately 6% more grout volume to account for possible inconsistencies (ground condition or pumping rate)

Figure 3 displays the plots of thermal profile versus depth (left) and the corresponding plot of shaft diameter versus depth (right). Plotted on the right side of Figure 3 are also the calculated average diameter (black), the nominal (design) diameter (green), and the diameter corresponding to 6% reduction in radius (red) (for comparison). Please note that according to current standards of practice, the recommended acceptance criteria for TIP analysis results include less than 6% radius reduction and meeting minimum concrete cover criteria. The diameter was calculated based on the thermal profile and the measured concrete volume. The top and bottom roll-off temperatures were corrected using the hyperbolic tangent curves as indicated. The thermal profile with depth is generally uniform suggesting that there was no significant defect in the installed shaft. There were small local bulges at approximately 6.5 m and 16.5 m depth. These locations reflect subsurface conditions with relatively softer consistency or loose subsurface conditions and hence providing less resistance to the grout pressure. In general, softer or less dense (than the grout) subsurface conditions result in local bulges while stiffer or denser soils result in local reduction in cross-section, all other factors remaining the same.



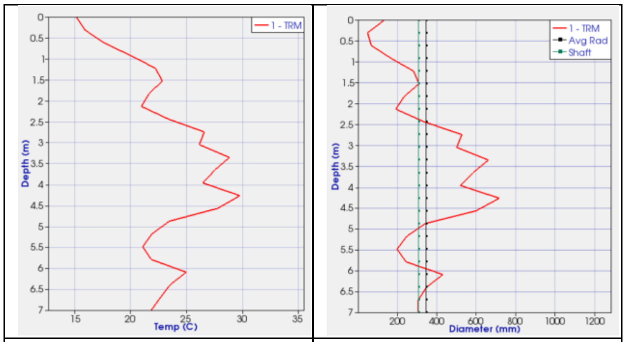
Temperature vs. depth

Diameter vs. depth

Figure 3. Example 1 TIP test results

The second TIP test example is for a case of ground improvement where the existing subsurface condition was weak and highly compressible. The ground improvement included the installation of Rigid Inclusions. This involved laterally displacing the weak / soft soil by advancing a displacement tool (typically a mandrel). As the mandrel is extracted from the ground carefully, grout mix is pumped at the bottom while maintaining positive grout head.

A single string of thermal sensors was installed through the centre of the mandrel. Once the grout was poured and the mandrel was extracted, a datalogger was connected to the thermal sensor string to monitor the hydration of the concrete (grout).



Temperature vs. depth

Diameter vs. depth

Figure 4. Example 2 TIP test results. Note: TRM in above plot indicates that some of the bottom sensors were 'trimmed' during analysis since longer than required thermal cable was installed.

Figure 4 shows the results of TIP test example 2. The soil improvement depth was approximately 7 m. Please note that the top 2 m of the subsurface soil has been reworked and loosened up (and subject to freezing ground condition) and thus the temperature measurement in this section is not considered representative of the existing subsurface condition at the site.

For the TIP test example 2 results presented above, the proposed ground improvement was to achieve a nominal (average) diameter of 300 mm and achieve a minimum of 175 mm. The plot on the left in Figure 4 indicates that the grout temperature at peak is significantly greater than the average peak hydration temperature of 23.5 °C between 2.5 and 4.5 m depth. Review of the subsurface information reveals very loose condition (blow count of zero per 0.3 m) as identified during subsurface investigation. As a result, there was substantial displacement of the very loose soil by the grout, even though the grout pressure was constant throughout the depth of ground improvement. The time to reach peak hydration temperature was approximately 11 hours. Hence, the thermal profile was able to quickly identify locations of weaker ground conditions where more material was required to be pumped to improve the ground.

In summary, both examples presented above demonstrate that TIP testing using the wire method was able to provide the required field quality assurance within a time frame of 24 hours.

6 STATUS OF TIP TESTING IN THE USA

Table 4 summarizes the status of TIP testing of deep concrete foundations. The summary shows the number of state DOTs in the USA and the status of TIP testing specification. Since transportation infrastructure projects are amongst biggest installers of deep foundation elements, the summary focused only on state Departments of Transportation. The summary is based on the information received from PDI (Zammataro, personal communication, 2018) and is up to date to summer of 2018. This information is presented to provide the general state of acceptance of TIP testing among DOTs in the USA. It is fair to say that TIP testing is gaining widespread acceptance or being evaluated more closely in the USA, as a possible replacement for other more established integrity test methods such as CSL.

Table 4 indicates that approximately 80% of the state DOTs have in some form adopted (or are evaluating) TIP testing as a viable quality assurance method for cast-in-place deep foundation elements. Currently, no published information is available on the trend of increasing acceptance of TIP testing internationally; it is inferred that the trend in many countries is similar to that in the USA.

Table 4 Summary of TIP status in the USA for state DOTs[1]

TIP status description	No. of state DOTs
Permanent specification available	2
Draft permanent specification available	8
Special specification available	15
Under evaluation	14
No information available (NA)	11
Total	50

[1] Summary based on information obtained from PDI (2018)

7 CONCLUSION

The more conventional methods of quality assurance for concrete deep foundations have significant limitations. The newest of all the methods, namely, thermal integrity profiling (TIP), seems to be increasingly gaining widespread acceptance among the piling community. It is likely that in the near future, it will replace other more established methods (such as CSL) as the quality assurance method of choice for cast-in-place concrete deep foundations. This is due mainly to relative ease of installation and data collection, and early detection of defects.

8 ACKNOWLEDGEMENTS

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