A brief overview of testing of deep foundations

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ABSTRACT: Deep foundations provide the key support for most heavy structures. The final product often is highly dependent upon the skill of the installing contractor and the success of the installation can be greatly influenced by the surrounding soils. It is imperative that these foundations function properly or the supported structure will be put into distress. The foundation must have adequate geotechnical capacity and its structural integrity must not be compromised. Unfortunately, the final foundation product lies buried beneath the ground which makes inspection difficult.

The foundations may be installed by drilling or driving methods. Because each installation technique has its own difficulties, different inspection methods, each with its unique strengths, are needed. Modern tools are now available to assess most deep foundations, either as monitoring during installation or inspecting the foundation in place. Several methods of integrity evaluation are available, and their applicability to the differing deep foundation types are discussed, and recommendations made. Static or dynamic testing methods are reviewed for their ability to assess the geotechnical capacity of each deep foundation type.

1 INTRODUCTION

The ultimate strength of a deep foundation must satisfy both structural and geotechnical limits for the foundation to perform as desired. Driven piles can be evaluated by dynamic testing for geotechnical ultimate capacity as well as installation driving stresses, structural integrity and hammer energy transferred to the pile. The same equipment can also be used for testing drilled shafts (bored piles). Other than static load tests which are performed according to ASTM D1143 (ASTM 2007), dynamic testing is the only common method used to estimate capacity from measurements. The cost of dynamic testing is significantly smaller than the costs of static tests, typically on the order of one tenth the cost. As the testing loads increase, dynamic testing becomes increasingly cost effective.

While individual drilled shafts (and augered CFA piles) can have their capacity verified by dynamic testing, untested shafts are assumed to have similar geotechnical capacity if they are of similar nominal size and length in similar soils. Because the installation process is unique for each, with no way to inspect the concrete placed in an open hole, it is often desired to know the structural integrity of a large percentage of piles on site and dynamic testing of such large numbers is then not usually practical. There are fortunately several alternative methods to evaluate integrity of these foundations, depending on goals and installation methods for the different drilled foundations. This paper will briefly review alternatives.

2 DRIVEN PILE CAPACITY

Dynamic pile testing (DPT) of driven piles was first routinely developed following research at Case Western Reserve University conducted between 1956 and 1977. DPT involves measuring pile force and pile velocity, usually near the pile top, as described by Rausche et al. (1985) with a Pile Driving Analyzer®. Guide specifications for performing the test correctly are given in ASTM D4945 (ASTM 2010). Testing is now commonly performed with wireless transmitters, and often by engineers at a location remote from the actual project location (Likins et al. 2009). “Signal matching” CAPWAP® software (Rausche et al. 2010) uses the measured input and an assumed soil model to create a calculated response that is compared with the measured response. The soil model is iteratively adjusted, often automatically, until the calculated and measured responses agree to obtain the full soil model, including the static resistance and its distribution along the pile shaft and toe. Correlations of CAPWAP results with static load tests (Fig. 1) have proven the method reliable as shown by Likins and Rausche (2004). Continued improvements in computation power now allow signal matching in real time during testing (Likins et al. 2012).

Pile capacity may change with time after installation of the pile. Capacity is often lower during driving due to pore pressure effects or arching effects from lateral pile movements; these capacity reductions are temporary and capacity then increases as pore pressure effects dissipate or as the normal earth pressures are restored. This capacity gain, described by Bullock et al. (2003) is generally called "set-up". Komurka (2004) has shown how set-up can be used both technically and economically to provide the lowest cost solution.

Prior to 2007, the American Association of State Highway and Transportation Officials (AASHTO 1992) guidelines for factors of safety (F.S.) in allowable stress design (ASD) were the following:

- 3.5 for dynamic formula
- 2.75 for wave equation analysis
- 2.25 for dynamic load testing
- 2.0 for static load testing
- 1.9 for static plus dynamic load testing

These single factors contain both the reliability of the determination method to estimate the capacity, as well as provide for uncertainty in the expected loads.

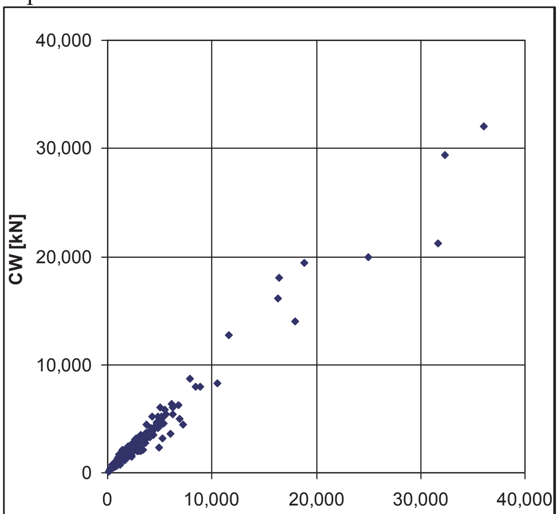

Figure 1. CAPWAP (CW) correlation with Static Load Test (SLT) after Likins and Rausche (2004).

The low testing cost to benefit ratio in reducing foundation costs through a lower safety factor has resulted in worldwide acceptance of dynamic testing. The value of testing can be illustrated by an example. Suppose we have a 40,000 kN load to support and that the ultimate pile capacity is 2,000 kN. Dividing the pile capacity by the factor of safety (F.S.) for each method of capacity determination yields a design load per pile and dividing the design load into the total load yields the number of piles required to support that load. This is shown for the AAHTO ASD factors in Table 1.

Table 1. Number of piles required for example case for AASHTO ASD method (prior to 2007).

Determination method	F.S.	Design load kN/ pile	# of Piles required
Dynamic formula	3.5	571	70
Wave equation	2.75	727	55
Dynamic testing	2.25	889	45
Static testing	2.0	1000	40
Static & Dynamic testing	1.9	1053	38

These ASD factors of safety produced successful designs for several decades of highway bridge construction. There was no specific guidance for the amount of static or dynamic testing.

Beginning in 2007, Load and Resistance Factor Design (LRFD) was required by AASHTO (2010) for highway construction in the USA. In LRFD the factor of safety is split into two components. The loads are multiplied by "load factors" to reflect the uncertainty of different load types (e.g. Dead, Live, Wind, Seismic…) and different combinations of loading cases are considered. The capacity is multiplied by a "resistance factor" (Φ) to reflect the uncertainty of the capacity determination method and site variability.

For the example case chosen and a typical dead load (D) to live load (L) ratio of 3, the typical controlling load combination is 1.25D + 1.75L, and the 40,000 kN total load becomes a factored load of (30,000 x 1.25 + 10,000 x 1.75) = 55,000 kN. The example pile capacity (2,000 kN) is multiplied by the resistance factor, and the number of piles required is then determined as shown in Table 2.

Comparing the numbers of piles required for a design by ASD in Table 1 with the number required by LRFD in Table 2 shows the number required by LRFD is only slightly less (max difference 8%). The equivalent factor of safety can be computed from the average load factor divided by resistance factor. Other noted differences are that Gates (Hannigan et al. 2006) is the only accepted dynamic formula, the amount of testing is specified, and testing all piles dynamically is considered the equivalent of one static test (per site condition).

Table 2. Number of piles required for example case for AASHTO LRFD.

Determination method	Φ	Equiv F.S.	Factored resistance kN / pile	# of piles req'd
Gates formula	0.40	3.44	800	69
Wave equation	0.50	2.75	1000	55
Dynamic test (min.2% or 2#)	0.65	2.12	1,300	43
Static test **or** 100% Dynamic test	0.75	1.83	1,500	37
Static test **and** >2% Dynamic test	0.80	1.72	1,600	35

The reduction in number of piles for the testing methods is justified considering the following:

- Most static tests have considerably more reserve strength beyond the Davisson criterion usually used to evaluate static tests for driven piles .
- Set-up is very common (even in sands) and adds extra safety for driven piles beyond static tests run after only modest wait times, or dynamic tests performed at end of drive or during a restrike after at most a few days.
- Production piles always meet or exceed the driving criterion (e.g. driving to a required 47 blow/foot, often the pile experiences 47 blows well before the full foot).
- Production pile driving results in densification of the soil, improving previously driven piles.
- Preliminary designs often overestimate the actual loads. Few piles are actually critically loaded, yet all are driven to the same higher load criterion. The number of piles in a group is rounded up (8.4 piles required is rounded to 9).
- Production piles generally are driven to a "blow count" criterion conservatively established by the test piles, effectively removing site variability.
- "Signal matching" (CAPWAP) is required by AASHTO for dynamic tests and has been shown to be conservative (Likins and Rausche, 2004).

There is a considerable difference between dynamic testing 2% of all piles and testing 100%. Consideration should be given to an intermediate resistance factor for an intermediate amount of testing (e.g. testing 25% might justify a Φ of 0.70). Individual state Departments of Transportation (DOT) may adopt their own guidelines. Ohio DOT uses Φ of 0.70 for dynamic testing of typically 2 piles per structure (so 40 piles would be required in our example), and the testing cost for Ohio DOT has averaged less than 2% of the piling costs over the last 5 years (Narsavage, 2011). Since the total cost of the foundation is generally proportional to the number of piles required, the significant reduction in number of piles demonstrated in Table 2 when piles are tested shows the clear economic benefit of the testing (43 piles for dynamic testing instead of 69 piles for Gates formula is a 38% savings; or 100% dynamic testing is a 46% savings over Gates), justifying the small 2% cost of the testing.

3 DRIVEN PILE MONITORING

The energy (E) transferred to the pile is computed from the measured force, F, and measured velocity, v.

$$E(t) = \int F(t)\, v(t)\, dt \qquad (1)$$

The maximum energy transferred during impact is then determined. Sufficient energy transfer assures both an efficient installation and that the pile can be installed to a proper depth for the required capacity. The blow count, or set per blow, is usually part of the installation criteria determined by the test pile program, so it is critical that energy transferred to production piles be similar to the test piles.

Driven piles must have adequate geotechnical capacity, but they also must have adequate structural strength. Usually the structural strength exceeds the geotechnical strength as long as the pile is not damaged during the installation process. Controlling the stresses during pile driving is important to prevent damage. Dynamic testing measures the compressive force at the pile top and allows computation of compression and tension stresses below the pile top. Maintaining driving stresses during installation below safe levels compared to the material strength will generally prevent damage.

Dynamic testing can be used to investigate specific suspect piles for the possibility of damage. For most piles with reasonable length, the velocity is positive throughout the first 2L/c time period (where L is pile length and c is the material wave speed). In this case the velocity times pile impedance should monotonically decrease relative to the force for this first 2L/c. If a local relative velocity increase occurs, particularly if the increase is sudden, then this represents a tension reflection from a reduction in cross section.

This concept is illustrated by Figure 2 for a pile before and after damage. The data show blows just prior to (#476) when some damage has occurred at the section (indicated by arrows), and just after (#477) the pile breaks. The solid vertical lines indicate the initial impact time and 2L/c later.

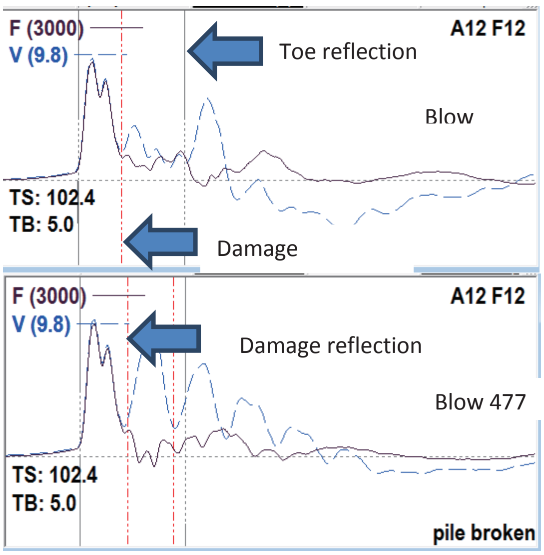

Figure 2. Dynamic testing reveals a pile that is damaged and then breaks completely.

Monitoring installation by dynamic testing for all blows during driving allows for a complete diagnosis of the pile condition to both prevent damaging stresses, assure that the hammer is performing normally, and to confirm that the capacity required has been reached.

4 INTEGRITY TESTING OF DRILLED PILES

Drilled foundations are not easily inspected, and their quality is related to soil conditions and the skill of the contractor. They are designed by static analysis methods with conservative soil strength assumptions, so their geotechnical capacity is not questioned. However, the foundation is still subject to compression or lateral failure if there is a significant structural weakness.

Drilled shafts often have large axial and lateral capacities but little redundancy making integrity of each shaft very important. As both dry and wet drilled shaft construction methods lack certainty in inspection, the possibility of defects in the shafts is large. O'Neill and Sarhan (2004) found 20% of shafts have defects.

Augered CFA piles are often installed with minimal inspection and defects are common. During the important concreting phase, the drill position is estimated from markings on the leads and the concrete volume is calculated from counting pump strokes. Ideally, the rig operator withdraws the auger from the hole by controlling the number of pump strokes for each depth increment. However, many project records show calculated volume only for the total pile rather than by critical incremental volume as specified by DFI (2003).

5 LOW STRAIN INTEGRITY TESTING

One of the earliest and most widely used NDT (Non-Destructive Test) methods to evaluate structural integrity is pulse echo or low strain testing. The top of the shaft is impacted by a hand-held hammer and the response measured by an accelerometer attached to the shaft (ASTM 2007b).

Early tension reflections before 2L/c are the result of major deficiencies. Figure 3 shows a sample result for two neighboring piles. The first record shows initial impact and the return from 2L/c of the pile toe at 25 m. The second record exhibits an early reflection from a depth of 15 m. In extreme cases the defect is so large that multiple reflections for many defect cycles are found and the toe reflection is not observed.

Data are normally enhanced by various signal processing methods to bring out record details (Likins and Rausche 2000). The shaft impedance profile can be estimated in marginal cases as in the present example to better quantify the size of the defect.

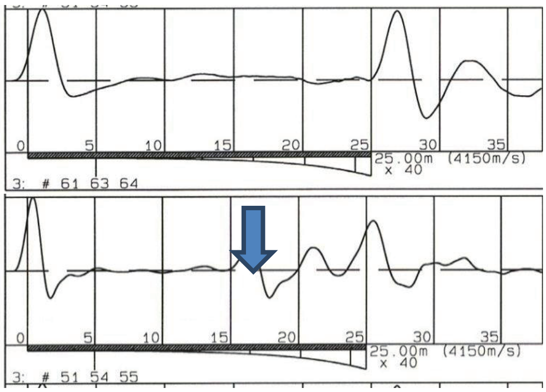

Figure 3. Low strain records of two piles. Top pile is acceptable. Bottom pile has major defect (arrow).

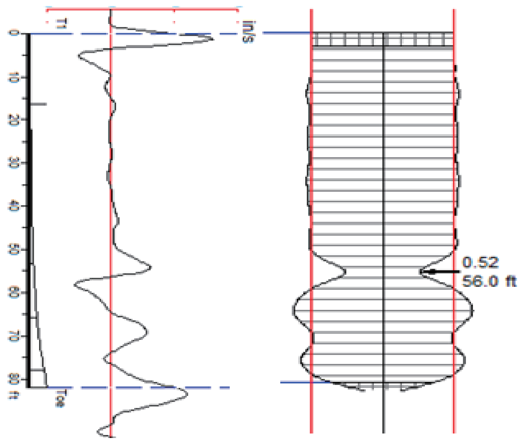

Figure 4. Profile of the defective pile.

Figure 4 shows a profile for the defective pile shown in Figure 3. It should be noted that after the first major defect the subsequent signals from the pile section below the defect may contain extra reflections due to the first defect and become less reliable. However, since the first major defect is the most critical and likely to cause pile failure the integrity assessment of the lower portion of pile below the defect is almost inconsequential.

6 AUTOMATED MONITORING EQUIPMENT

Augered CFA piles are often installed with minimal inspection, increasing the chance for defects. During the important concreting phase, the drill position is crudely estimated and the concrete volume is calculated from an assumed volume for each pump stroke, "calibrated" at low resolution (e.g. perhaps as few as 6 strokes for a 55 gallon barrel). If recorded manually, depth resolution typically is only every 5 ft (1.5 m). However, many project records show calculated volume only for the total pile with no indication at all of the critical incremental volume as specified by DFI (2003).

Mechanical pump operation may be inconsistent over time. When pump failures occur, significant reductions in pile cross-section occur as there is no way to know when the pump is not supplying the assumed volume per pump stroke. Often an inconsistent pump will produce little or no concrete for many consecutive strokes, leading to severe necking within the pile.

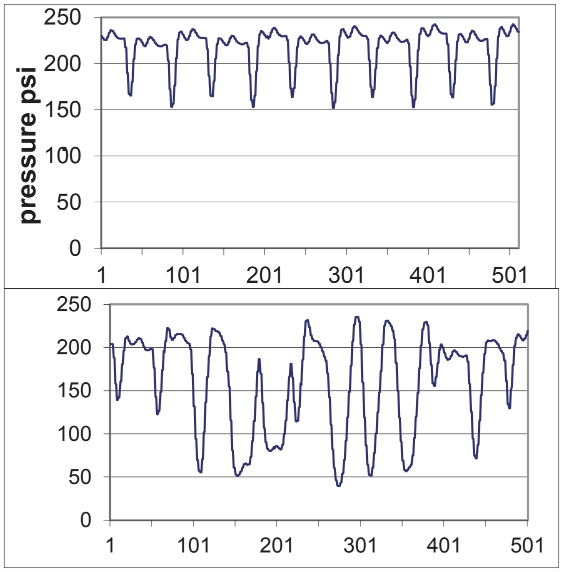

Figure 5. Pressure measurements versus time: top shows normal operation, bottom is faulty pump.

Figure 5 illustrates both a proper performance and a faulty performance of the same pump on the same pile. The concrete volume delivered to the pile and verified by the flowmeter measurements during the seven faulty pump strokes was considerably less than the volume calculated from the pump stokes.

Quality of augered CFA piles is greatly improved by Automated Monitoring Equipment (AME). AME is specified in many codes including the Federal Highway Administration GEC#8 (Geotechnical Engineering Circular No. 8) (Brown et al, 2007). GEC#8, for example, requires 2 ft (61cm) depth increment accuracy and a magnetic flowmeter to measure volume.

AME monitors key elements of both the drilling and concreting phases. During drilling, AME monitors auger tip position, auger rotations, torque pressure, crowd pressure, and auger advancement speed. During the critical concreting phase, AME monitors depth and volume to obtain "incremental concrete volume" (called the most critical quality control parameter by the Deep Foundation Institute) (DFI, 2003) and concrete pressure. Volume is accurately measured by the magnetic flowmeter rather than estimated by pump strokes.

The AME, installed in the rig, provides feedback to the rig operator to guide the drilling and concreting operations. During drilling, AME provides the auger tip penetration depth and torque pressure, assuring the piles are drilled to the correct depth. During concreting AME guides the operator to fill each increment of the pile.

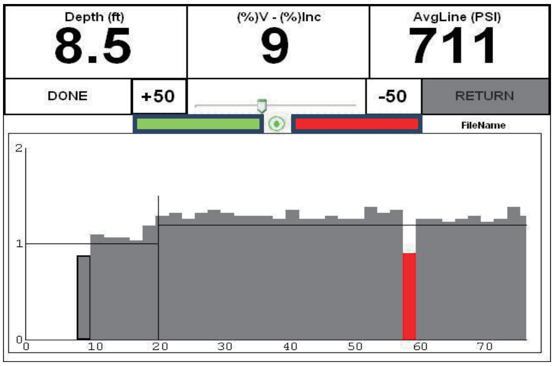

Figure 6. AME screen showing void at 60 feet.

Figure 6 shows the AME concreting screen which guides the operator in real time. The horizontal line in the bar graph is the minimum concrete target value (typically at least 115% of theoretical volume). If any increment is under-filled, the increment is displayed in red. Such violations immediately alert the operator to correct the deficiency by re-drilling and re-concreting the pile before exiting the hole. Once the concrete is seen at the ground surface (vertical line shown at 20 ft in Fig. 6), the target line reduces to 100% of the theoretical volume as per DFI guidelines (DFI 2003). The sliding bar in the upper portion of the screen displays the optimum pulling speed to guide the rig operator.

AME records all pertinent drilling and concreting parameters and provides a field printout for immediate review by the Engineer or Inspector. If any under-filled depth increments are discovered, remedial action can be immediately taken while the pile is still fluid. This allows for immediate acceptance of the piles by qualified site personnel or, if voids or other problems occur, they can be immediately identified and rectified before the auger is completely withdrawn.

7 CROSSHOLE SONIC LOGGING (CSL)

Drilled shafts are commonly tested by CSL. Procedures are described in ASTM D6760 (ASTM 2008). Several access tubes (one for each 0.3 m of shaft diameter) are attached to the reinforcing cage prior to casting concrete. Several days after casting a transmitter probe is lowered into one tube and a receiver probe into another tube. The probes are generally kept at the same elevation and pulled simultaneously from bottom to top of the shaft to evaluate the concrete along the full shaft length. Probes are then moved to other tubes and the test repeated for all tube combinations.

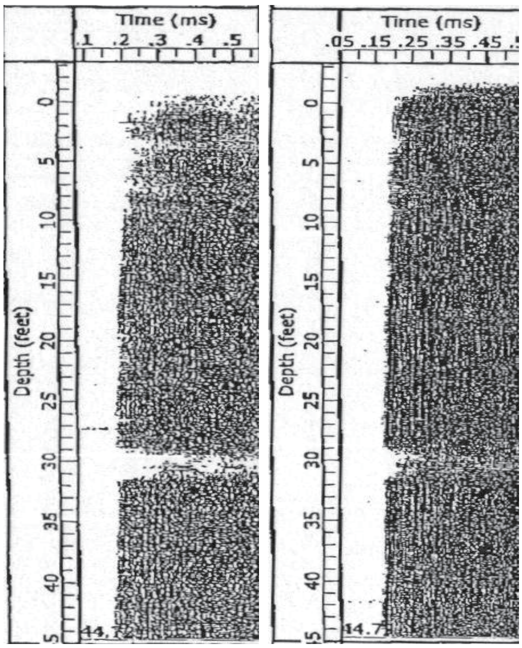

Figure 7. Tests of shaft with defect at 30 ft (9m);
Left is initial test; Right is after pressure grouting.

Analysis of the data is described by Likins et al. (2007). Figure 7 presents the waterfall diagram which is a nesting of the raw data. The left edge is the "first arrival time" (FAT) and is the most important feature. The intensity of the graph reflects the signal strength; the white at 9 m (30 ft) indicates a defect. The left half of the plot is the initial test performed a few days after casting. Since basically the same graph was obtained for all tube combinations, the defect is a layer through the entire section. A core was then specified and is shown in Figure 8. The shaft was pressure grouted using the core hole, and the shaft was tested again (right half of Figure 7). While the defect is still observed, its severity was greatly reduced and the shaft was accepted.

Figure 8. Core of defective shaft showing defect.

The advantages of CSL testing are many. Construction may be performed more carefully when the possibility of definitive testing is possible. CSL is independent of the pile length or surrounding soil, and the first major defect does not affect measurements at deeper depths along the shaft. CSL allows detection and quantification of multiple defects, and can determine the quadrant of the shaft where the defect is located.

However, CSL also will not detect defects unless they penetrate the cage, so loss of cover is not detectable by this method. Construction is delayed until testing is completed and the shaft approved, and since testing can only be accomplished in solid concrete several days after casting, this delay can be significant.

8 THERMAL INTEGRITY PROFILING (TIP)

Thermal Integrity Profiling (TIP) measures the heat of hydration along the shaft length to evaluate the entire cross-section, including determination of the concrete cover (Mullins 2010). The thermal method is not limited by length or by non-uniform shaft profiles.

The normal heat signature at the cage of curing concrete depends on the shaft diameter, concrete mix design, soil conditions, and time after concrete casting. The average temperature at any particular depth at any time after casting is nominally proportional to the effective radius of the shaft at that depth, with the exception of locations within one diameter from either the top or bottom of the shaft where heat transfer to the surrounding soil is not exclusively radial.

Any deficiency in the concrete (e.g. void, necking or simply weak concrete strength) results in less heat producing cement at that location and will interrupt the normal temperature signature, with cooler temperatures near this defect. Any higher temperature than the average indicates an increased concrete volume (bulge).

In addition to determining shaft integrity of the core or cover, thermal testing evaluates the reinforcing cage alignment by comparing measurements from radially opposite locations. If one location is cooler than the average at some depth and the radially opposite location is warmer, this indicates that the cooler measurement location is closer to the surrounding soil while warmer measurement location is closer to the shaft center.

Temperature measurements can be made either by a thermal probe if access tubes are available, or by attaching wires with a series of thermal sensors to the reinforcing cage prior to casting concrete. One measurement should be made equally spaced around the reinforcing cage for each 0.3 m of shaft diameter.

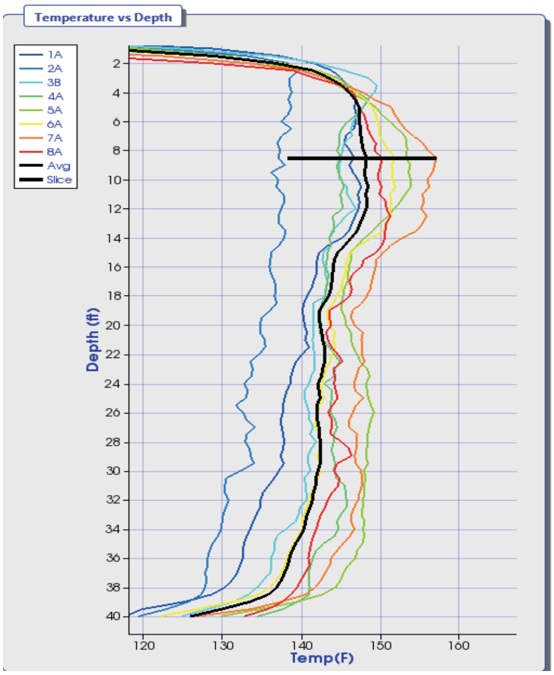

Figure 9. Field data showing cage misalignment.

Temperature measurements using a thermal probe via each access tube should be made near peak temperature, typically 12 to 48 hours after completion of the shaft. The optimum time depends on the shaft diameter and mix design. Larger diameter shafts or mix designs with high slag take longer to reach peak temperature.

If thermal sensing wires are embedded in the shaft, they are tied to vertical members of the reinforcing cage. Thermal measurements are taken automatically at regular time intervals (typically every 15 minutes) at least until the shaft has reached its peak temperature.

The overall average temperature of the shaft is proportional to an average shaft radius, which is directly computed from the total concrete volume installed.

The shaft shown in Figure 9 contains eight access tubes through which this thermal probe data was obtained. The data indicates that the tube labeled 2A is considerably cooler than the average temperature, and therefore significantly closer to the surrounding soil indicating less cover. The tubes opposite (5A, 6A, and 7A) are warmer than the average at this depth slice selected indicating they are all closer to the shaft core. Thus, the cage has an alignment issue. The average data shows no local cool zones with a normal temperature roll-off at the bottom of the shaft, and hence no local defects are present in the shaft.

Compared to CSL, thermal testing accelerates the construction process. If no issues are found, then casting caps can proceed immediately after testing, often within 24 hours of casting the shaft.

9 SUMMARY AND CONCLUSIONS

Dynamic pile testing is now a routine procedure for evaluating driven piles and can be applied to drilled shafts. Signal matching of the data is generally required for this testing by most codes and produces a detailed soil model including total capacity with resistance distribution as well as a simulated static load test curve. Compression stresses are measured, and compression and tension driving stresses along the entire shaft length are computed. Based on knowledge of stresses, the hammer system can be adjusted to prevent pile damage. Dynamic testing easily detects damaged piles.

Different codes recognize that testing reduces uncertainty. More accurate test methods and larger quantity of testing results in lower safety factors for ASD and higher resistance factors for LRFD, with the result that the better testing practices results in fewer piles or shorter piles for any given design, and thus a significant reduction in foundation costs.

Since drilled or augered shaft construction introduces uncertainty, evaluation of shaft integrity is a key consideration in shaft performance and acceptance. Several integrity evaluation methods are available.

For augercast piles, low strain integrity testing with an accelerometer attached to the top of shaft to measure the response of a small hammer is quite common. The test works best for relatively uniform shafts, and should be used to investigate only for major defects. The first major defect generally renders the shaft as unacceptable but also prevents evaluation of the remainder of the shaft below the defect. A better solution for augered piles is to prevent defects by use of Automated Monitoring Equipment including a flowmeter so that concrete volumes are accurately recorded.

CSL tests are commonly used to evaluate the integrity of larger drilled shafts. CSL can locate multiple defects and identify their locations both in depth and cross section quadrant. However, detection of defects in the concrete is limited to defects that penetrate the cage and affect the core. Concrete cover cannot be assessed.

The thermal method uses the heat of hydration during concrete curing to evaluate the entire cross section, including both core and cover of drilled shafts. Defects of any kind result in relatively cool temperatures near the defect. Because thermal testing has its best application at peak temperatures, testing is performed and results available often within 24 hours of casting the concrete; for good shafts, this speeds the construction process.

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