QUALITY MANAGEMENT BY MEANS OF LOAD TESTING AND INTEGRITY TESTING OF DEEP FOUNDATIONS

Evgenia-Anna Sellountou, Ph.D., and Frank Rausche, Ph.D., P.E.

Pile Dynamics, Inc., Cleveland, Ohio, USA

Summary.

This paper presents several methods for an economical assessment of the geotechnical and structural quality of driven and bored piles. Full scale load test methods for the determination of pile capacity include conventional static load tests, dynamic load tests, bi-directional static load tests and rapid load tests. In this presentation, dynamic load testing will be emphasized. This method is based on measurements of force and motion taken under the impact of a large mass. These so-called Case Method measurements are then subjected to a rigorous analysis (CAPWAP®) to calculate static pile capacity. The method accounts for both the static and dynamic components of the soil response and thus determines resistance distribution, damping factors and soil stiffness. Dynamic pile load testing background and its application in both driven and bored piles are discussed herein. Pile load testing assures that the geotechnical conditions are sufficient for a satisfactory pile performance. Because of time and cost limitations, these tests are normally conducted on only a few special test piles or on production piles if questions arise during construction. However, to assure adequate structural quality, integrity testing is another important component of a complete quality management program. While driven piles can be damaged during installation, cast-in-situ deep foundation elements are susceptible to flaws or defects due to improper construction methods. High Strain integrity testing (e.g., during pile driving or in the form of dynamic load testing sometime after pile installation), Low Strain (also called Pulse-Echo) integrity testing and cross-hole sonic logging are the most common non-destructive testing (NDT) techniques used worldwide. An emerging and very promising NDT method is the so-called Thermal Integrity Profiler (TIP). It is based on temperature measurements taken during the curing of the concrete of cast-in-situ piles. Temperature signatures provide information about potential bulges, necks and the reinforcement cage alignment. Brief summaries of these NDT methods will be presented herein.

1. Introduction

Geotechnical capacity estimation and structural integrity confirmation are fundamental requirements in the design of deep foundation elements. Preliminary capacity estimates based on static analysis methods are usually confirmed on-site by full scale load tests. The two most common methods of full scale load testing for the determination of capacity are static load tests and dynamic load tests. Other full scale load test methods include bi-directional static load tests and rapid load tests. This paper will focus on the dynamic load test method. The dynamic load test is commonly employed during the installation of driven piles for both capacity determination and installation monitoring purposes (monitor driving stresses, hammer performance, pile structural integrity etc.). Bored piles can be tested in a similar fashion for the purpose of determining capacity and structural integrity.

Dynamic load test has a significantly lower cost compare to a static load test. Unlike a static load test, dynamic testing does not require reaction piles and a reaction frame. Usually several piles can be installed and dynamically tested in a single day unlike static load tests which typically require several days to test a single pile (installing the test pile and reaction piles, assembling the reaction frame and test arrangement and performing the static test which in itself may require at least several hours and sometimes a few days). Dynamic load testing becomes particularly important on large sites with variable soil conditions where it can address variations in capacity and driving conditions and where the use of only static load tests would be cost prohibitive. Capacity estimate comparisons between static and dynamic load tests are referenced below.

Untested shafts are assumed to have similar geotechnical capacity when installed in the same manner and in similar soil conditions as the test piles. However, in-situ elements are susceptible to imperfections and creation of defects during installation. Construction under slurry, improper concreting procedures, heavy reinforcement that impedes concrete flow, borehole instability and other factors during construction can jeopardize the structural integrity of a shaft. Although the structural integrity of a shaft is indirectly verified through load testing, it is practically impossible to load test a large number of shafts as would be needed on large projects. Fortunately, non-destructive methods are available to test the integrity of bored piles. The two most commonly used methods are the low strain integrity testing and the cross-hole sonic logging (Rausche, 2004 [10]). However, a recently developed method, the Thermal Integrity Profiler (TIP) (Likins and Mullins, 2011 [8]), which uses temperature measurements of the curing concrete inside the shaft to assess concrete quality and shaft shape, is a very promising emerging technology and will also be briefly described in this paper.

2. Dynamic Load Testing-Basic Principles

In the United States, dynamic load tests are performed in accordance with ASTM D4945 [3]. To perform the test, strain transducers and accelerometers are attached near the top of the pile (**Figure 1**) to measure strain and acceleration that are induced in the

pile top under the impact of a hammer. Wireless and smart sensors which transmit their calibration values to the recording Pile Driving Analyzer® (PDA) system, shown in **Figure 2**, are often remotely monitored, allowing the engineer to analyze the data in real time from the office.
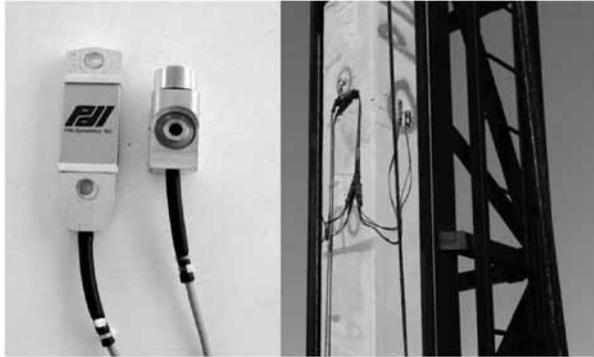

Figure 1: Wireless (left) and wired (right) stain gauges and accelerometers attached at the pile top

Figure 2: PDA with Antenna

The principles behind dynamic pile testing are based on one-dimensional wave propagation theory (Rausche et al., 1985 [12]). Under the impact of a hammer a stress wave is induced at the pile top that propagates down the pile at a wave speed (c), until it reaches the tip after which, is reflected back up the pile. The wave speed depends on pile properties only, namely on elastic modulus (E), and density (ρ) of the pile material and is independent of the characteristics of the impact force. The time for the compression

stress wave to travel down to the pile tip and be reflected back up to the pile top is 2L/c (L being the length of the pile). The type and magnitude of the wave up reflection depends on the type of resistance encountered at the pile tip. Moreover, soil resistance and pile section changes cause upward stress wave reflections at time prior to 2L/c. The downward and upward traveling waves at any time, t, and at any location, x, along the pile can be analyzed by the total measured particle force and velocity at that location. As mentioned above, strain gauges and accelerometers, attached near the top of the pile, generate electronic signals of strain and acceleration that are converted to force and velocity by, respectively, multiplication with the elastic modulus, E, and cross sectional area, A, and integration over time (**Figure 3**).

Referring to Timoshenko and Goodier, 1970 [14], if the force in a traveling wave is F, the particle velocity, v, can be expressed as

$$v = \frac{c}{EA}F. \qquad (1)$$

This relationship expresses a proportionality between particle velocity and applied force, with the proportionality constant being composed of pile material properties i.e. E, A, and c (defined above). The inverse of the proportionality constant, called pile impedance, Z, is defined as

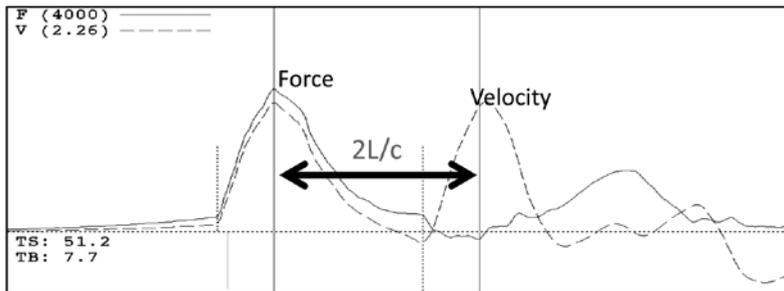$$Z = \frac{EA}{c}. \qquad (2)$$

Figure 3: Force-Velocity signals from PDA

The pile impedance is a term associated with the resistance that the pile offers to "impede" the change in its velocity. The impedance, Z, has units of force divided by velocity (kN/m/sec) and represents the force that is required to change the pile particle velocity by 1 m/sec.

The total force and velocity measured at any pile location are the result of superposition of the forces and velocities in the upward and downward traveling waves. Based on equations 1 and 2, and remembering that compression force and downward

particle velocity are positive, a simple system of equations can be solved for the particle force in the upward and downward traveling waves, $F_\uparrow$ and, $F_\downarrow$:

$$F_\downarrow = \frac{F_m + Zv_m}{2}, \qquad (3)$$

$$F_\uparrow = \frac{F_m - Zv_m}{2}. \qquad (4)$$

This means that at any point in time we can calculate the force at wave up and force at wave down at a certain location based on the measured force (F_m) and measured velocity (v_m) at that location (in our case near the pile top). For a pile struck by a ram, the combination of all upward traveling waves contains the activated soil resistance and the bottom reflected impact wave. We, therefore, can calculate the total soil resistance (shaft and end-bearing), activated by the impact, as follows:

$$R_{Total} = R_S + R_B = F_{\downarrow @ t_1} + F_{\uparrow @ t_2}, \qquad (5)$$

or

$$R_{Total} = \frac{F_{m1} + Zv_{m1}}{2} + \frac{F_{m2} - Zv_{m2}}{2}. \qquad (6)$$

Time t_1 is often chosen such that the resulting resistance values are a maximum and time t_2 is $t_1 + 2L/c$. The total resistance (R_{Total}) is comprised of a dynamic component ($R_{Dynamic}$) (dependent on the velocity of the penetrating pile) and the displacement dependent static component (R_{Static}), which is of ultimate interest to us. Therefore,

$$R_{Static} = R_{Total} - R_{Dynamic}. \qquad (7)$$

The dynamic component can be calculated by introducing a viscous damping parameter (J_v) that associates the dynamic resistance component with the velocity at the pile toe as follows:

$$R_{Dynamic} = J_v v_{toe} \qquad (8)$$

where,

$$v_{toe} = \frac{2F_{\downarrow @ t_1} - R_{Total}}{Z} = \frac{F_{\downarrow @ t_1} - F_{\uparrow @ t_2}}{Z} \qquad (9)$$

Combining equations 5 through 9, the static resistance can be calculated from the measured particle force and velocity (at the gauges near the top of the piles) as follows:

$$R_{static} = (1 - Jc)\frac{F_{m1} + Zv_{m1}}{2} + (1 + Jc)\frac{F_{m2} - Zv_{m2}}{2}, \qquad (10)$$

where, (J_c) is the non-dimensional Case damping factor, given by:

$$\mathbf{J_c} = \frac{J_v}{Z} \tag{11}$$

The Case damping factor typically varies with soil grain size from 0.4 to 1.0 for non-cohesive to cohesive soils, respectively. Equation 10 is the so-called Case Method for determining static pile capacity from a dynamic test, i.e. a test, which requires the measurement of force (strain) and velocity (acceleration) during the impact of a hammer. The impact from a hammer could be part of the installation process in case of a driven pile, or, in case of cast-in-situ foundation elements, e.g. bored piles, would be provided by a special purpose drop weight, solely for the purpose of dynamically testing the element. The Case Method, as described above, gives a first estimate of static pile capacity. The dynamic measurements of strain and acceleration are then subjected to a more rigorous analysis (Rausche et al., 1985 [12]) to calculate static pile capacity with greater accuracy. The so-called CAPWAP method is a signal matching process (or reverse analysis procedure), in which the measured input and an assumed soil model is used to obtain a calculated response that matches the measured input. Soil model parameters are adjusted until a good agreement between measured and calculated signals is obtained. More specifically, CAPWAP assumes that the soil reaction consists of elasto-plastic and viscous components which means assigning three unknowns at each discrete point of the soil model i.e. the ultimate static resistance, the quake of the soil (elastic soil deformation) and the damping constant. The CAPWAP analysis is completed when these three unknowns are determined for each point along the shaft and the toe of the pile.

Dynamic measurements and analyses, i.e., the dynamic load test, of deep foundations as described above not only provides information on soil resistance, but also on dynamic compressive and tensile stresses in the pile during driving, hammer performance and pile integrity or damage. During pile testing, stresses are monitored by the PDA to prevent damage. Obviously, the pile top compressive stresses are simply determined from the strain measurements. However, maximum tension stresses, occurring below sensor location, and pile toe compression stresses have to be calculated and closed form solutions exist for that purpose. In addition, CAPWAP signal matching can be used for both uniform and non-uniform piles to assess stresses for any point along the pile.

While stress monitoring helps prevent pile damage of driven piles, damage or defect assessment can be done by the so-called β-Method. The quantity, β, is the ratio of damaged to undamaged cross section and can be evaluated, given an impedance reduction caused tensile reflection, normalized by the downward traveling impact wave, α (Rausche and Goble, 1979 [11]).

$$\boldsymbol{\beta} = \frac{1+\alpha}{1-\alpha} \tag{12}$$

The PDA formula is somewhat more elaborate and considers the effects of soil resistance above the damage location which reduces the intensity of the impact wave.

Hammer performance, finally, is most easily done by calculating the energy transferred from the hammer to the pile. This involves an integration of the product of force and velocity over time. The maximum value of the resulting curve is often referred to as ENTHRU in the literature; divided by the rated hammer energy yields the so-called transfer ratio, transfer efficiency or global efficiency. Statistical evaluations of the transfer ratios for different hammer and pile combinations have been published (Rausche and Klesney, 2007 [13]).

3. Dynamic Load Testing-Driven Piles

Dynamic measurements and analyses are indispensable tools, today routinely employed during pile driving operations for the monitoring and testing of driven piles. The PDA, field instrumentation system (**Figure 1** and **Figure 2**) and CAPWAP software (**Figure 4** shows a typical result page) from Pile Dynamics, Inc. are used every year on thousands of construction sites worldwide for data collection and data interpretation.
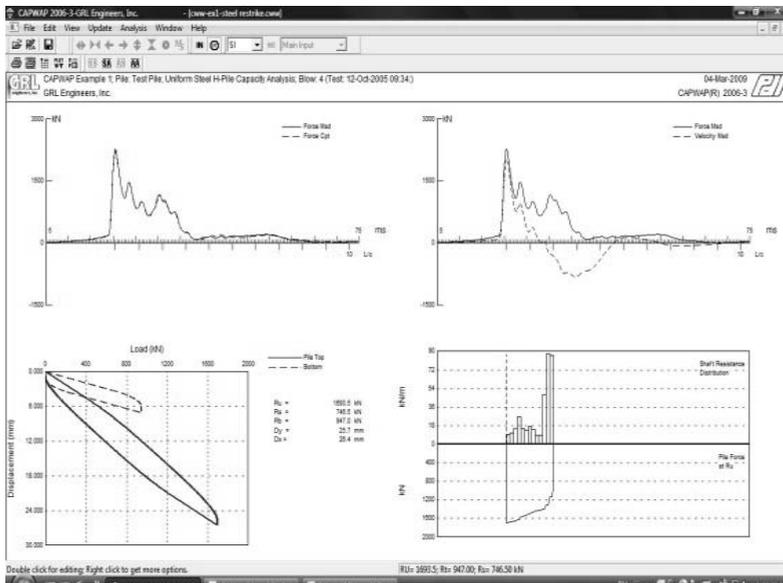

Figure 4: CAPWAP Software Screen Shot

Dynamic pile testing provides capacity estimates to a large percentage of piles both during the load test program as well as during actual construction. Multiple piles can be installed and economically tested within a single day. Capacity determination of an adequate number of piles is particularly important when piles are installed on large sites with variable soil conditions. Dynamic testing allows evaluation of potential variations

335

of capacity and driving conditions across large construction sites, where performing sufficiently many static load tests would be cost prohibitive. Dynamic testing is also very effective in achieving an optimal foundation where modern design and construction codes allow for reduced overall factors of safety as a function of the number of tests performed. For example, the Load and Resistance Factor Design approaches of the EC 7 in Europe or AASHTO in the United States specify more economical partial safety factors or resistance factors as a function of the number of dynamic tests performed.

Apart from capacity determination dynamic pile installation monitoring provides information about hammer performance and driving system efficiency, In general, compressive and tensile stresses induced during driving have to be kept below an acceptable limit to avoid cracking and/or otherwise damaging the pile. In the United States, the highway authorities, for example, allow steel compressive stresses to reach 90% of yield, while concrete compressive stresses are limited to 85% of concrete compressive strength minus prestress. The tensile stresses in regularly reinforced piles should be kept to below 70% of the yield strength of the reinforcement. Tension in prestressed piles can be taken to the prestress level plus 50% of the concrete tensile strength.

Poor hammer-to-pile alignment can induce excessive eccentricity and therefore high bending stresses that could be detrimental to the pile integrity. An underperforming hammer may be unable to drive the pile in the required penetration, or can result in unacceptable driving times and overstressing of the pile. Moreover, differences in the transferred energy between the production piles and the test piles will alter the driving criterion. A PDA is capable of monitoring these effects, blow by blow during driving, as well as asses pile damage if that occurs during driving.

Dynamic pile testing during driving mainly focuses on the determination of driving stresses, pile performance and pile integrity. The capacity determination from EOID (end-of-initial-driving) provides a short-term pile capacity estimate, which very often (depending on the soil conditions) is lower than the long-term pile capacity. More specifically, piles driven into cohesive soils induce an increase in the pore water pressures in the surrounding soil during driving that only slowly dissipate with time. As the excess pore water pressures dissipate the pile capacity increases. This phenomenon is commonly referred to as soil "setup". For that reason restrike tests are performed for the determination of long-term pile capacity after an adequate waiting period from the time of installation. For comparisons of static with dynamic load test results, the waiting period for the restrike test should be similar to that for a static load test and, ideally, shortly after the static test has been performed. It should be mentioned that the drilling process of cast-in-situ piles also affects the strength of the pile-soil interface material and requires sufficient waiting times before testing will take place. Of course, the concrete also has to be gaining enough strength before a dynamic (or static) load can be safely applied.

Many researchers and practitioners have published correlations of long-term capacity estimates as determined by static load tests and restrike dynamic tests for a variety of soil conditions and pile types. These studies show the dynamic restrike tests to be very reliable in determining long-term static pile capacity and that CAPWAP results and

static load tests results are in excellent agreement if waiting times for the two test types are comparable. A recent compilation of a large database of driven and bored piles has been presented by Likins and Rausche, 2004 [9]. In this paper two previous major studies (performed in 1980 and in 1996) and studies individually reported in six Stress Wave conferences are all compiled in a single document, resulting in the analysis of 303 cases. Statistical analysis of the combined database showed the average CAPWAP/(Static Load Test) ratio to be 0.98 with a coefficient of variation of 0.169. Since the average CAPWAP to Static Load Test ratio is less than unity, and the often used Davisson evaluation of static load tests is less than other commonly used failure criteria, CAPWAP is, on the average, conservative.

4. Dynamic Load Testing-Bored Piles

As mentioned, dynamic load testing is also routinely used for the capacity determination of cast-in-situ elements. Again, the PDA system and CAPWAP software are one of the most common systems to be utilized worldwide for that purpose. A main difference between driven pile testing and bored pile testing is that the former is usually tested by using a pile driving hammer (diesel, hydraulic, air-steam etc.), whereas the latter is tested by means of large drop hammers with only a few, well controlled impacts for better stress and energy control.

Typically, three to five hammer impacts are performed for a successful dynamic load test on a bored pile. Recommendations on ram weight, drop height (stroke) and cushions are given by Hussein et al., 1996 [7]. Typically a ram weight of 1% to 2% of the required capacity is utilized. The drop height and therefore the applied energy is increased from blow to blow until an adequate set (permanent displacement) for the mobilization of the capacity is reached, without the stresses exceeding the allowable limits. Around the world many different types and weights of drop hammers have been specifically developed for dynamic pile testing. Their ram weights and maximum drop heights vary between 2 to 80 tons and 1.5 to 3 m, respectively. They are dropped either by mechanical or hydraulic free release devices or simply by brake release of the crane winch. Guiding of the drop weight may be done by external frames (preferable for larger weights) or by center guiding rods which are fixed to a plate on top of the pile. **Figure 5** shows a picture of the APPLE drop hammer by GRL Engineers, Inc., used in United States, whose drop weights can range from 1 to 40 tons and which feature an external guiding frame with hydraulic ram release.

Figure 5: Apple Drop Hammer

An interesting application, out of the numerous applications worldwide, of dynamic testing of drilled shafts, is the Lee Roy Selmon Crosstown Expressway in West-Central Florida, described by Hussein et al. , 2008 [6]. The dramatic failure of one of the drilled shafts during the construction of the aforementioned expressway in Florida in 2004, which resulted in structural collapse of two bridge spans, severely shook confidence and mandated a thorough investigation of the entire project. Twelve completed bridge piers were dynamically tested with a very large scale testing configuration as can be seen in **Figure 6**. The forensic foundation study resulted in remediation action of 154 out of the 218 pier shafts (Anderson and McGillivray, 2006 [2]). Additional drilled shafts and micro-piles were added at several pier locations. About two years after the dramatic failure incident and after all remediation work was completed the project opened to the public without any incident since then.

Figure 6: Hammer on Pier, Lee Roy Selmon Crosstown Expressway

5. Integrity Testing of Bored Piles

Cast-in-situ deep foundation elements are particularly susceptible to structural defects and imperfections. They are not easily inspected, usually are designed to carry large loads, and often have little or no redundancy. In other words, often single piles are used to support columns with high loads. Confirming the structural integrity of bored piles is, therefore, of utmost importance. While dynamic tests can be used to verify structural integrity of bored piles as described above, untested shafts are assumed to have a geotechnical capacity similar to the tested ones if they are of the same size, are installed in the same soil conditions and with the same construction procedures. However, this assumption is not valid for structurally defective shafts. It is therefore important to confirm the structural integrity of bored piles. Several NDT methods have been developed and successfully utilized for the evaluation of the structural integrity of deep foundations. The most commonly used methods are Crosshole Sonic Logging and the Low Strain Integrity Testing. A recently developed and very promising technology is the Thermal Integrity Profiler.

In the United States, Crosshole Sonic Logging (CSL) is performed in accordance with ASTM D6760 [5]. In Europe, other standards exist, e.g. AFNOR, 2000 [1]. To

339

execute this test, access tubes made of PVC or steel, having internal diameters of typically 50 mm are attached to the reinforcing cage prior to concreting. Several days after casting, the CSL test is performed by lowering in parallel tubes an ultrasonic pulse transmitter and a receiver probe, respectively. Based on the signal's first arrival time (FAT) at the receiver tube and on the energy of the received signal, defects in the concrete located in the paths of the wave pulses can be detected. Both FAT and signal energy can be automatically determined; tube distance divided by FAT yields a measure of concrete quality. **Figure 7** shows a typical record of one scan in the form of a so-called water fall diagram and the derived wave speed and signal energy curves. In the example, a loss of the signal near the bottom is attributed to a so-call soft toe condition.
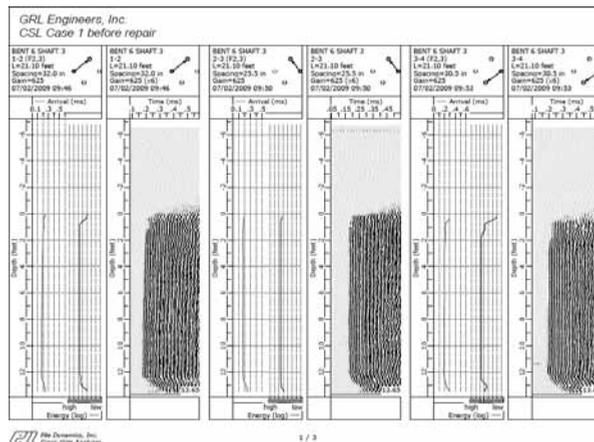

Figure 7: CSL Test Results revealing a soft toe situation (Water Fall Diagram, FAT and Energy Curves)

Because of this finding, a core hole was drilled in the shaft and with a video camera the photo shown in **Figure 8** was taken. It clearly shows the defective condition at the pile bottom.

Figure 8: Defect seen from a core hole

Using a mathematical procedure called tomography the wave speeds measured between all available combinations of tubes can be further analyzed to yield two- and three-dimensional images. For a shaft installed with planned defects for research purposes in the yard of Pile Dynamics, **Figure 9** shows both a vertical section and a 3-D result. The blue color represents unacceptably low wave speeds.
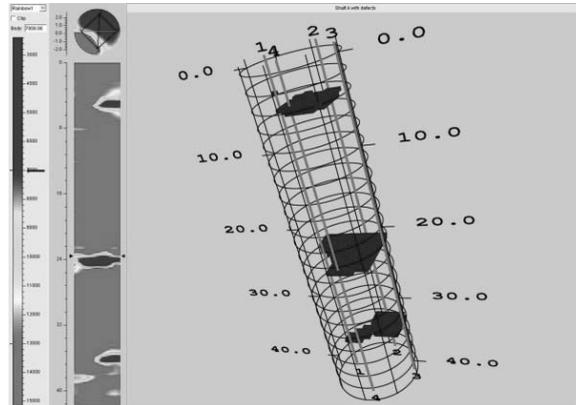
Figure 9: Tomography display of CSL records showing defects

Obviously, the test provides clear results for even very great depths (CSL has no depth limitations). However, it only indicates concrete quality variations which are located between inspections tubes. Thus, while the CSL method yields generally very clear and detailed results about the concrete quality between the transmitter and receiver probes, it does not provide any information about the concrete outside of the reinforcement cage and, therefore, cannot be used to assess the size or quality of the concrete cover. Another limitation of CSL testing is that the access tubes have to be pre-planned. So if during construction a shaft is considered potentially defective it cannot be tested with CSL if access tubes were not installed during reinforcement cage placement.
The latter limitation of CSL is overcome by another commonly used NDT method, the so-called Low Strain Integrity Testing or Pulse Echo Test (ASTM D5882 [4]). Unlike CSL test, Low Strain Integrity Testing does not need any pre-planning in order to be utilized for pile integrity evaluation. Therefore, is particularly helpful in cases where integrity testing of finished shafts is required but CSL access tubes have not been pre-installed. The Low Strain Integrity testing or Pulse Echo Test, incorporated in the PIT equipment, requires that a light hand-held hammer tap is applied to the pile top. The impact creates a compressive stress wave of low intensity. An accelerometer is temporarily attached to the pile top to measure the pile top motion due to impact and reflection waves. **Figure 10** shows a test being conducted with a wireless accelerometer and a very small receiving, PIT-X, unit which displays and stores the received signals.

Figure 10: PIT Testing Configuration

The low strains generated by the light hammer impact and the associated low displacements generated by the traveling wave cause only a minimal resistance reaction in the soil and it is for that reason possible to receive at the pile top reflections from the pile toe when the soil embedded pile length is up to about 45 times the diameter of the pile. In very competent soils it may only be possible to see a toe reflection from a depth of 20 diameters. Apart from the length limitation, this method is very quick and relatively inexpensive and can be applied to any concrete pile (maybe also timber piles of limited length) since it does not require any preparations (such as inspection tubes). Often all piles in a project are tested by this method due to its cost effectiveness. **Figure 11** shows the velocity vs. time records of two piles, the first having no defect and the second one with a clear reflection prior to the toe signal which indicates that there was an impedance reduction.
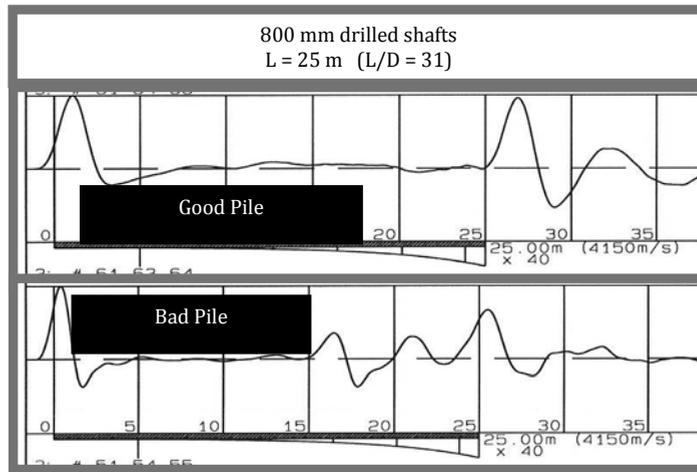
Figure 11: PIT testing Output

A new and very promising NDT method for pile integrity evaluation is the Thermal Integrity Profiler (TIP). TIP, a rapidly emerging technology, presents many advantages over the current-state-of-practice methods i.e. CSL and PIT described above. More specifically, TIP does not present length limitations, it can evaluate pile integrity within few hours of shaft construction, it offers 100% testing coverage of the pile cross sectional area (including the area outside the cage), and it provides extra information e.g. cage misalignment and therefore concrete cover. The theoretical soundness of the method and the ease in performing the test and interpreting the results makes it attractive and increasingly popular within the engineering community. The TIP approach is based on concrete temperature measurements during hydration of the concrete, i.e., within a short time period after the concrete has been poured. The basic principle behind TIP is that a perfect, uniform concrete cylinder with a reinforcing cage placed symmetrically within the cylinder will provide uniform temperature profiles with depth, in locations equidistant from the center of the cylinder. The presence of defects or cage misalignments will alter the temperature signatures. Defects and misalignment can be quantified based on the temperature profiles and concrete volumes information. Temperatures can either be measured with infrared probes in inspection tubes, the same that also could be used for CSL testing. Alternatively, Thermal Wire® brand cables could be installed along the reinforcement cage and they can continuously monitor the concrete temperature. A simple evaluation procedure can produce a 3-dimensional image of the pile, given the installed volume of the concrete. **Figure 12** shows both the derived profile of the shaft (including the location of the reinforcement cage) and the temperature vs. depth of a 2.13m diameter shaft, instrumented with six (6) Thermal Wire cables. A photo of the actual shaft after excavation is also shown in the same figure.

343

This result shows rather clearly that the higher temperatures near the top and thus the depiction of the bulge have their origin in the actual pile shaft geometry which also includes an eccentricity of the reinforcement cage.
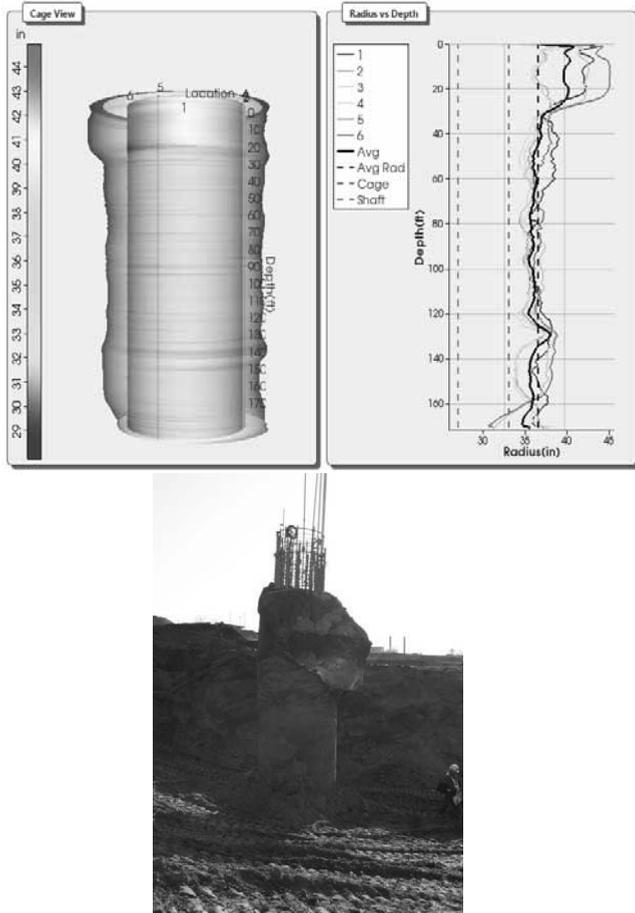
Figure 12: Profile as derived by TIP including location of the reinforcement cage (top left), temperature vs. depth profiles as measured by Thermal Wire cables (top right), and a photo of the actual shaft (bottom).

6. Summary

This paper described a number of methods, which with the exception of the Thermal Method are based on measurements of stress wave propagation. The most important one, the high strain test (dynamic test), is useful for both the monitoring of driven piles during installation and dynamic load testing of driven and bored piles. Monitoring the pile installation by measuring pile top force and velocity with a PDA is a construction control procedure; it helps to avoid pile damage by maintaining safe driving stresses and, should damage happen anyhow, does not only detect it, but does also quantity its magnitude. Dynamic monitoring also provides information about the Static Resistance to Driving (SRD). While for certain soils the SRD at the end of installation is identical to the long term pile capacity, in soils which are sensitive to dynamic loading, a restrike is necessary to perform a meaningful Dynamic Load Test. Evaluated by CAPWAP both long term soil resistance and its distribution along the pile and a simulated load-set curve are obtained. Primarily for drilled shafts but also for other concrete piles, assessment of the structural integrity of the shaft is part of a complete Quality Assurance program. Two traditional methods, Cross Hole Sonic Logging and Pulse Echo have now been joined by the Thermal Integrity Profiler. While all methods have benefits and limitations, TIP is a promising new technology which overcomes many shortcomings of the more traditional methods.

REFERENCES

1. AFNOR, -*XP P94-152 Sols: reconnaissance et essais – Auscultation d'un élément de fondation – Partie 1: méthode par transparence*-, Association Française de Normalisation, 2000, France (in French)

2. Anderson, S. and McGillivray, R. -*Under the Crosstown: Remediating the Drilled Shaft Foundations for Tampa, Florida's Lee Roy Selmon Crosstown Expressway*- Foundation Drilling Magazine, June/July 2006, pages 10–14.

3. ASTM D4945, -*Standard Test Method for high-strain dynamic testing of deep foundations*- American Society for Testing and Materials, Philadelphia, PA, Construction Vol. 4:08

4. ASTM D5882, -*Standard Test Method for low-strain impact integrity testing of deep foundations*- American Society for Testing and Materials, Philadelphia, PA, Construction Vol. 4:08

5. ASTM D6760, -*Standard Test Method for integrity testing of concrete deep foundations by ultrasonic crosshole testing*- American Society for Testing and Materials, Philadelphia, PA, Construction Vol. 4:08

6. Hussein, M.H., Bullock, P.J., Rausche, F., and McGillivray, R. -*Large-scale Dynamic High-Strain Load Testing of a Bridge Pier Foundations*- Proceedings of the Eighth International Conference on the Application of Stress Wave Theory to Piles, Lisbon, Portugal, 2008, pages 371-377.

7. Hussein, M.H., Likins, G. E., and Rausche, F. -*Selection of a Hammer for High-Strain Dynamic Testing of Cast-in-Place Shafts*- Proceedings of the Fifth International Conference on the Application of Stress-wave Theory to Piles, Orlando, FL, 1996, pages 759-772.

8. Likins, G.E., Mullins, G., -*Structural Integrity of Drilled Shaft Foundations by Thermal Measurements*- Structural Engineer, November 2011, pages 46-48.

9. Likins, G.E. and Rausche, F. -*Correlation of CAPWAP with Static Load Tests*- Proc. of the 7th Int. Conf. on the Application of Stress Wave Theory to Piles, Petaling Jaya, Malaysia, 2004, pages 153-165.

10. Rausche, F. -*Non-Destructive Evaluation of Deep Foundations*- Proceedings of the 5th International Conference on Case Histories in Geotechnical Engineering, NY, 2004, CD-ROM.

11. Rausche, F., and Goble, G.G. -*Determination of Pile Damage by Top Measurements*- American Society for Testing and Material, Philadelphia, PA, 1979, pages 500-506.

12. Rausche, F., Goble, G.G., and Likins, G.E. -*Dynamic determination of pile capacity*- Journal of Geotechnical Engineering, Vol. 111, No. 3, 1985, page 367 – 383.

13. Rausche, F., and Klesney, A. -Hammer Types, Efficiencies and Models in GRLWEAP- PDCA 11th Annual International Conference and Exposition, Nashville, TN, 2007, pages 97-118.

14. Timoshenko S.P., and Goodier J.N. -*Theory of Elasticity*- McGrow-Hill Book Company, 3rd edition, NY, 1970.