Pile and shaft integrity test results, classification, acceptance and/or rejection

Corresponding Author
Karen Webster,
GRL Engineers,
9912 Colvard Circle
Charlotte, N.C.
704 593-0992
Fax 704 593-0993
kwebster@pile.com

Frank Rausche,
GRL Engineers, Inc.
30725 Aurora Road
Cleveland, OH 44139
216 831-6131
Fax 216 831-0916
frausche@pile.com

Scott Webster
GRL Engineers, Inc.
9912 Colvard Circle
Charlotte, N.C.
704 593-0992
Fax 704 593-0993
swebster@pile.com

4300 words
2 Tables
3 Figures

Submission date: August 1, 2010

ABSTRACT

For the quality assurance of cast-in-place deep foundations (cast-in-drilled-hole shafts (CIDH) and augered-cast-in-place (ACIP) piles) a number of different methods exist, all with certain advantages and disadvantages. Because of physical limitations, none of these methods provide complete certainty of the strength and estimated service life of the foundation element under the various service loads. This paper examines two commonly employed NDT methods, Cross Hole Sonic Logging (CSL) and Low Strain Testing (LST), both of which rely on sonic pulse wave propagation and/or reflections to assess concrete quality. The authors present a framework for decision making in the face of less than fully conclusive NDT test results. Application of this framework is demonstrated in several case studies showing test results and mitigation approaches.

INTRODUCTION

The concrete quality of cast-in-place deep foundations is frequently as much of concern as the geotechnical quality of the foundation element. The latter is generally assessed by load testing of one or more test specimens and the assumption is made that the test piles have been installed in representative soil layers and with construction methods identical to the production piles. On the other hand, because of construction difficulties due to unforeseen problems, every production pile is vulnerable to different structural problems. Such structural problems are of significance if detected by NDT *(1)* and should be dealt with either by evaluating their effect on the structural shaft capacity or through mitigation. A variety of potential defects of special concern exist. For axial capacity, the quality of the shaft throughout its length is important and, for end bearing piles or those with a rock socket, the shape of the pile just above its toe is of concern. Of equal importance for large shafts, designed to support high lateral loads, is the thickness and quality of the concrete cover. The latter is also of concern when soil conditions are aggressive and the reinforcement needs protection against corrosion.

Several methods exist *(2)* to evaluate a drilled shaft's structural integrity after the concrete has hardened. The most commonly employed method in the transportation related construction practice is the Cross Hole Sonic Logging Method (CSL). Less frequently specified is the Low Strain Test (LST), although this is more prevalent in the building industry than in transportation. Also the acceptance of these two methods varies considerably from country to country.

The CSL Method (ASTM 6760-08) is the most commonly employed non-destructive test method in the US transportation industry. It requires sending out a high frequency pulse in one inspection tube and measuring its arrival time in a neighboring tube. If the wave arrives late, relative to neighboring cross sections, or if it is of significantly reduced signal strength, then concrete located between the tubes is considered to be of lower quality. The inspection tubes are usually mounted inside and along the reinforcement cage and, for that reason, generally will not give information about a defect in the concrete cover. However, defects such as a major soil inclusion in the concrete, such as a "soft toe" (concrete/mud mixture) or a conical pile toe shape can be easily detected.

The LST method has the advantage that it can be applied to any shaft or concrete pile without requiring a special preparation such as the installation of inspection tubes. This method has existed since the 1970s. LST, standardized by ASTM 5882, primarily relies on the measurement of the pile top motion following a light hammer impact. Stress wave reflections from increases or decreases in shape or concrete quality along the pile are registered by the measurements at the pile top and then interpreted by the test engineer. If, for example, the cross section sharply decreases at a certain distance below the pile top, then at a time which depends on the distance of that reduction from the top, a velocity increase will be registered. It is not clear from the velocity record alone whether or not the reflection originates from a defect in the center of the pile, from the reduction in concrete cover thickness, or from a section of reduced concrete strength.

Neither CSL nor LST can definitely identify a reduced concrete cover over the reinforcement. However, there are other methods that can help identify such defects, the oldest of which is based on a concrete density measurement by gamma rays. A more recently developed, very promising method which has the advantage of giving information during the very early time of concrete hydration is now referred to as the Thermal Integrity Profiler (TIP). By measuring the concrete temperature either in inspection tubes or discretely by thermo couple strings permanently installed in the concrete *(3)*, the method allows clear assessment of concrete quality without the need for radioactive probing.

CROSS HOLE SONIC LOGGING

Record Interpretation and Classification

The Cross Hole Sonic Logging Method has become more and more widely accepted and, at first sight, offers a very simple data interpretation. A strongly reduced Signal Energy (generally defined as the time integral of the square of the signal) and/or late signal First Arrival Time (FAT) suggest defective concrete. Depending on the severity of the relative reduction of Signal Energy or increase of FAT, a questionable quality can be defined and the piles and shafts can be categorized as proposed in *(4)* and shown in Table 1. This scale, based on the authors' experience, adapts a common scale used by many state departments of transportation. The adapted scale differentiates between a marginal flaw and a serious defect, while assigning actual numerical values to the Signal Energy reduction. Unfortunately, current USA practice often only adopts vague statements about signal energy while standards in other countries include signal energy in their assessment *(4)*.

TABLE 1 Recommended CSL concrete quality rating

Category	FAT Increase	AND / OR	Signal Reduction	Comment
G	Up to 10%	AND	< 6db	Good
Q	10 to 20%	AND	< 9 db	Questionable
P/F	21 to 30%	OR	9 to 12 db	Poor/Flaw
P/D	>30%	OR	> 12 db	Poor/Defect

Once a FAT increase or a Signal Energy reduction has been identified, their extent over the cross section has to be assessed. For example, in a shaft with 4 inspection tubes and, therefore, 6 possible profiles, a FAT reduction in only one diagonal affects a rather small portion of the cross section and, even if of the P/D type, requires no further investigation. It is, therefore, suggested that the shaft integrity is evaluated with the following scale:

- Questionable (Q) profiles require no further action but may be considered when P/F or P/D also occur in the same cross section.
- Flaws (P/F) should be addressed if they are indicated in more than 50% of the profiles.
- Defects (P/D) must be addressed if they are indicated in more than one profile and involving at least 3 tubes.

Specifications Concerning Mitigation after CSL

Addressing a flaw or defect should include, at a minimum, an evaluation by tomography (a three-dimensional assessment of the whole shaft). Tomography may take the form of a mathematical inversion analysis or a more direct determination through several horizontal and vertically offset scans. In this way, the area of concern can be localized and quantified supporting then the call for additional measures such as later retesting (after further concrete hardening), excavation, or core drilling with pressure grouting, if required.

Flaws indicated over a complete cross section either require that the shaft is used "as is" (possibly with a reduced capacity) or that it be remediated over the flaw area or be replaced. The bearing capacity can, however, be upgraded after load testing the pile either statically or dynamically. For large shafts it may be worthwhile to perform a dynamic load test which not only determines the geotechnical capacity, but also the shaft's structural strength. In the spirit of the LRFD design approach, it may be sufficient to subject the test shafts to a load which is lower than what the normal factor of safety would require if (a) all questionable shafts are load tested and (b) one or more properly constructed piles are tested for comparison.

Defects indicated over the entire cross section (i.e., if apparent in all scans) usually require repair or shaft replacement. Quality checks of the pressure grouting repairs may either be performed by additional

CSL tests and/or dynamic tests. Obviously, if a shaft has been designed without consideration of end bearing (i.e., as a pure friction pile) then a Flaw or Defect near the bottom of the pile can be ignored.

Example 1

CSL results for this 48-in (1.2 m) diam., 14-ft (4.3 m) long shaft indicated an apparent defect near its bottom. This apparent defect was indicated in all CSL profiles by FAT delays ranging from 25% to 55% (P/F and P/D) and extending over 1 foot (0.3 m) of the shaft bottom in all of the profiles. Indicated as a flaw or defect in all profiles, these findings had to be addressed. The tomography result in Figure 1 shows one vertical section and four horizontal sections at various depths near the pile bottom (see depth information above each plot and percentage of poor concrete in the horizontal cross section). The tomography result uses wave speed rather than FAT (wave speed = distance between tubes divided by FAT); it depicts the defect condition by black color for concrete with a wave speed of 10,000 ft/s (3,300 m/s) or less and red with wave speeds greater than 12,000 ft/s (3,660 m/s).

The severity of the defect was confirmed by means of coring at 4 locations which all found significant quantities of poor quality material at the shaft toe, likely due to the mixing of the shaft concrete with water during concrete placement. This material was removed through the use of high pressure water injections and suction. Grout was then placed in the bottom of the shaft to fill the generated void.

After the repair was completed (approximately 5-½ weeks after the first test), the shaft was again CSL tested. The testing still showed a concrete quality issue near the shaft bottom although at reduced FAT delays of between 14 and 38%. Such results are typical of a retest on a drilled shaft after pressure grouting due to the "cold joint" between the two different materials, their different curing times, and physical properties. To verify this, two additional cores were drilled to the bottom of the shaft. The core samples indicated good quality concrete and good quality grout. However, a thin layer of material with a slightly different physical appearance and an approximate thickness of 1 to 2 inches (25 to 50 mm) was present in one of the cores approximately 1 foot (0.3 m) above the bottom of the core. The core sample was fractured above and below this interface layer but the material within the layer appeared to be good quality concrete. A video taken from the boreholes after the poor quality material was removed showed concrete "fins" that could not be removed with the high pressure water jetting. The fins were extending from the outside edge of the shaft into the interior of the shaft. After another high pressure water jetting effort to remove a small amount of material from this core hole, both holes were filled with grout.

Approximately 2 ½ weeks after the repair was finished, the shaft was tested a third time and results similar to the second test were obtained. Again, these results were typical of a retest of a shaft that has had a pressure grout repair. Three of the six profiles indicated almost identical FAT delays (approximately 16%). The parties involved agreed that this signal arrival time delay could reasonably be attributed to the different physical properties of the two materials (grout and concrete) and be considered a baseline for comparison for the other profiles in the shaft. Subtracting 16% from the delays indicated in the remaining 3 profiles resulted in delays within the acceptable range (11 to 22%). The shaft was then accepted.

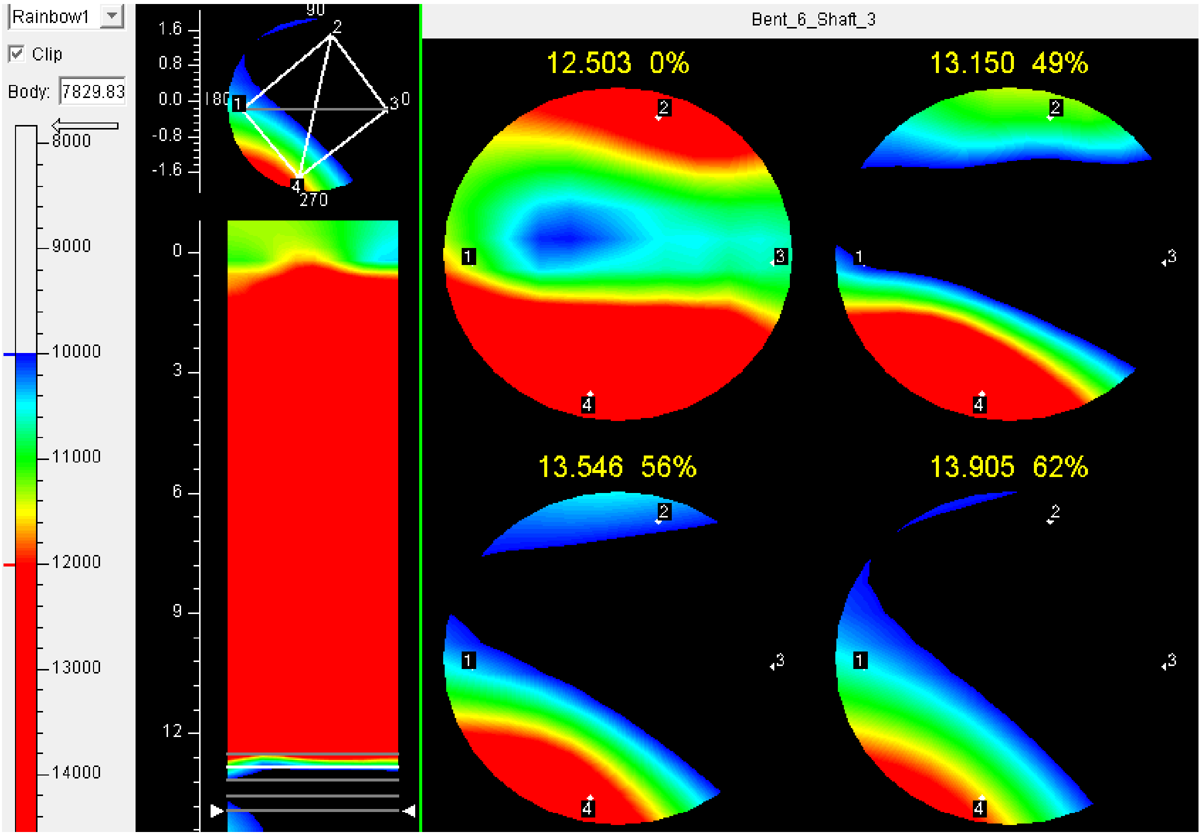

FIGURE 1 Tomography for Example 1 - Before First Repair.

Example 2

CSL results for this 36-inch (900 mm) diameter, 38-foot (11.6 m) long shaft indicated an apparent defect at a depth of approximately 36.5 feet (11.1 m) below the top of the shaft. This apparent defect was indicated in all of the CSL profiles by FAT delays ranging from 16% to 60% (Q, P/F, P/D). These results may suggest that either a soil intrusion had occurred near the shaft toe or that mixing of the shaft concrete with water or slurry occurred. Based upon the results it appeared that the indicated defect was likely most prevalent around one specific tube. This was indicated by the relatively normal FAT in two of the other profiles. However, since the defect was also indicated in one of the diagonal profiles not associated with this tube, it appeared that more than just a localized condition was present.

Based upon these CSL results, the shaft was cored and defective concrete was found in the area where the delays were indicated. This material was removed by water jetting and then the area was post grouted. A second CSL test performed approximately 6 weeks after the first test indicated FAT delays in the affected area ranging from 8 to 20%. Again, these delays were likely due to a “cold joint” between grout and concrete and due to the differences in the age and properties of the grout and concrete. The shaft was then accepted.

Example 3

CSL results for this 36-inch (900 mm) diameter, 29.5-ft (9 m) long shaft indicated an apparent defect at the toe of the shaft in all CSL profiles with FAT delays between 19% and 71% (Q, P/F, P/D) over the bottom 1 foot (0.3 m) of the shaft. Figure 2 shows the tomography result which depicts a deficient area with the black area denoting a wave speed of less than 10,000 ft/s (3,300 m/s). The black line near the bottom of the vertical section and the large black area in the horizontal section at 28.9 ft (8.8 m) in Figure 2 identify the areas of concern. The design engineer made a determination that the rock socket for the shaft exceeded the design depth and, therefore, no remediation was required.

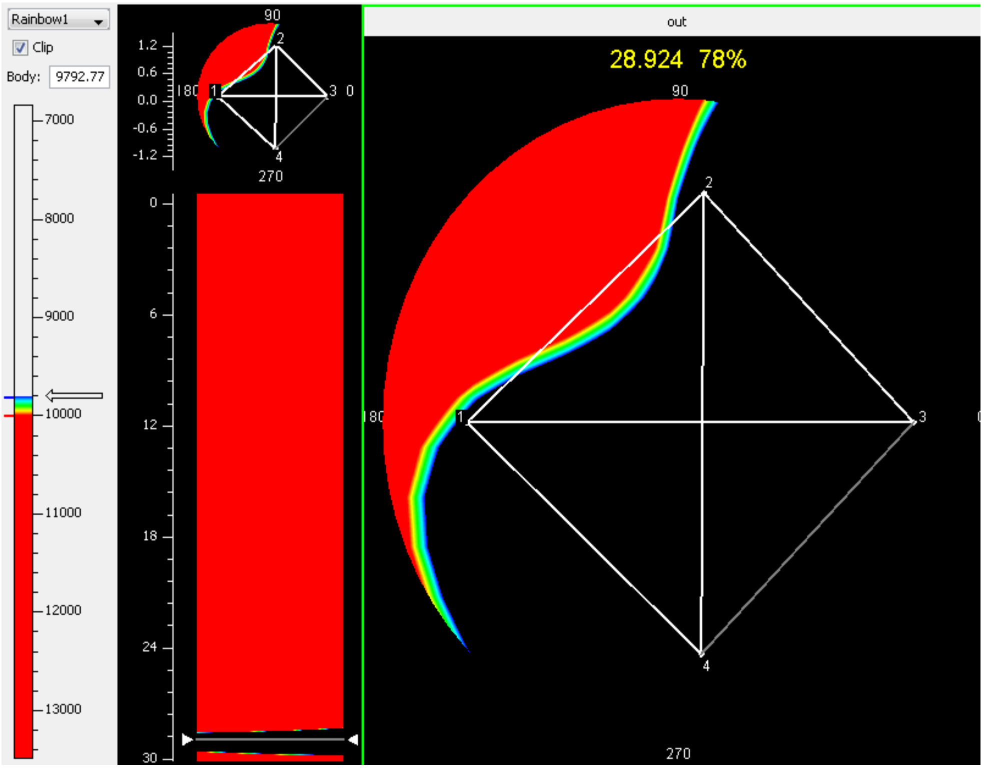

FIGURE 2 Tomography, Example 3 (1 ft = 0.305 m).

Example 4

CSL results for this 42 and 36-inch (1070 and 900 mm) diameter, 33-ft (10 m) long shaft indicated an apparent flaw at its toe. This 42-inch cased shaft section extended to a depth of approximately 11 ft (3.4 m) with approximately 7 ft (2.1 m) extending into the rock socket. Below this, the shaft diameter decreased to 36 inch (900 mm) with 12 ft (3.7 m) through rock and then 9 ft (2.9 m) into a silt layer. The apparent flaw was indicated in all six CSL profiles by FAT delays above 20% (P/F) and extended over 1 foot (0.3 m) of the shaft bottom. In order to determine the bearing capacity of the shaft, an extension was constructed above the top of the shaft and a 15 ton ram (approximately 2% of the required ultimate load) with guiding frame was used to apply dynamic loads of various energy levels to the shaft. A total of six impacts were applied with drop heights ranging from 12 to 42 inches (300 to 110 mm). The total set of the shaft after the six impacts was approximately 1/8 inch. As such, the average set per blow was quite small. Dynamic monitoring of the impacts was conducted by measuring forces and velocities with a Pile Driving Analyzer®. Results of the testing were further evaluated by modeling the actual shaft dimensions and signal matching with CAPWAP® indicating mobilized capacities between 1300 and 1530 kips (5800 to 6800 kN) for the higher drop heights. These results were considered sufficient evidence that the shaft met the ultimate load requirement of 1480 kips (6600 kN) and no mitigation was required.

LOW STRAIN TEST INTERPRETATION

Classification

As mentioned, this method requires impacting the pile top surface with a small, hand held hammer and measuring the resulting pile top motion. Not requiring the installation of several inspection tubes, this method is particularly useful for piles with diameters less than 30 inches (760 mm) or those for which no inspection tubes have been built into the shaft. The ensuing stress wave will travel along the pile and be reflected at the pile toe. Upon return to the pile top, it generally produces a motion at the pile top which is called the pile toe reflection. Reflections received at the pile top prior to the toe reflection are generally interpreted as variations of pile material quality or pile size; such reflections may, for example, be generated by the lack of sufficient concrete cover. Unfortunately, there is no distinction between reflections emanating from the side or the center of a shaft. For the determination of unknown deep foundation length, LST is useful and has been occasionally employed if a toe reflection is apparent. LST data interpretations are not necessarily a simple matter and depend heavily on the clarity of the reflections which diminishes as soil resistance and/or pile length increase.

Because of these difficulties the authors' company has proposed an expansion of the 4-category classification system proposed in 1994 *(5)*. The new, expanded system is summarized in Table 2.

Specifications and Mitigation after LST

To be useful, the LST specifications must clearly indicate the required actions for each of the classifications. Short of repair or replacement, the following actions may be taken if the test outcome is not an AA classification.

- For Category AB records where the test is inconclusive due to a great length or embedment, it may be sufficient to accept the shaft if the upper shaft portion appears to be of good quality. Obviously, the LST method is then at its limit and cannot make a more definite determination. Other test methods, if available, would need to be employed for more conclusive results.
- For Categories PF and/or PD indicating flaws or defects near the top, excavation around the pile may be done for pile inspection.
- For Category PF and/or PD, indicating flaws or defects at greater depths, a reduced pile capacity may be assessed based on conservative shaft property assumptions, including consideration of a reduced length. Analytical treatments of the data, e.g., by the Profile Method *(6)*, may provide helpful information. Also, the shaft may be retested later by LST (when the concrete has achieved greater strength) or by other methods (e.g. dynamic load testing).
- For Categories PF and/or PD, shafts of sufficient size may be cored to check their concrete quality. Core holes may then be used for CSL testing and/or repair by high pressure grout injection.
- For Categories PF and/or PD, piles which can be easily replaced (e.g., ACIP of moderate diameter), the piles should be replaced as quickly as possible. The authors have been involved in projects where these piles were immediately replaced at relatively low cost and practically no loss of construction time.
- For Category IV and IR records, additional LST testing may be scheduled (a) after removal of poor pile top concrete, (b) after allowing concrete to achieve greater strength or (c) when the cause of the vibration disturbance has been eliminated.
- For Category IV and IR records, if the specifications call only for a portion of the total number of piles to be tested, additional tests on other piles could or should be required as a replacement of the inconclusive ones.
- In order to interpret records correctly, it is recommended that analysts carefully study not only the low strain records themselves, but also construction records and soil profiles. In many instances reductions in pile size can be explained by the nature of the drilling procedure and/or soil characteristics. For example, where piles are drilled through soft into hard material, a cross sectional reduction in the harder material often must be expected. Thus, it is generally not recommended to base the acceptance or rejection of a pile solely on the LST records.

TABLE 2 Recommended LST record Classification concrete quality rating

Class	Class Name	Commentary
AA	**Sound shaft integrity indicated**	A clear toe reflection can be identified corresponding to the reported length and a wave speed within acceptable range; records in this category may indicate normally accepted variations of size or material quality.
AB	**No major defect indicated**	The records indicate neither reflections from significant reductions of pile size or material quality nor a clear toe response. Records in this category do not give indications of a significant deficiency; however, neither do they yield positive evidence of the shaft being flawless over its full length.
ABx	**No major defect indicated to a depth of x ft (m)**	Because of method limitations, interpretation of the record for the full length is not possible. For example, long piles or shafts and those with high soil resistance and/or major bulges fall under this category
PFx	**Indication of a probable flaw at an approximate depth of x ft (m)**	A toe reflection is apparent in addition to at least one reflection corresponding to an unplanned reduction of size or material quality. Additional quantitative analysis may help identify the severity of the apparent flaw.
PDx	**Indication of a probable defect at an approximate depth of x ft (m)**	The records show a strong reflection corresponding to a major reduction of size or material quality occurring; a clear toe reflection is not apparent.
IVx	**Inconclusive record below depth of x ft (m) due to spurious vibrations**	Data is inconclusive due to vibrations generated by construction machinery or heavy reinforcement extending above the pile top concrete; retesting is advisable under certain circumstances.
IR	**Inconclusive record**	• poor pile/shaft top quality or low concrete strength (test has been conducted too early); retesting after waiting and/or pile top cleaning is advisable, • planned impedance changes or joints generate signals which prevent toe signal identification.

Example 5

Specifications for a bridge widening project called for integrity testing on more than 100 shafts whose diameters ranged from 36 (900) to 48 in (1,200 mm). The pile tests were conducted over a time period of two years. Pile lengths were in the 30 to 60 ft (9 to 18 m) range. The piles were generally drilled through soft and weathered into sound claystone and/or sandstone. The project had a very demanding schedule and for that reason integrity testing by the Low Strain Method was preferred by the project management.

Of the almost 120 tests, 65% fell into the AA group. At the time of the testing, 26% were classified as inconclusive, because the records did not show a clear toe signal, but also no evidence of a defect. According to Table 2, these shafts would now be classified as Category ABx (no defect over the upper x ft (m) of shaft, but no toe signal, because of high soil/rock resistance) or as Category IVx (inconclusive records below a certain depth x, because shaft top surface vibrations interfered with the reflections from the pile toe). While 26% of these shafts did not provide positive evidence of a sound shaft, neither did they indicate any problems.

Six percent of the piles were classified as PFx because the records indicated a flaw which was quantified as to location and magnitude using the so-called Profile *(6)* calculation method which gives a somewhat idealized visualization of one possible shaft configuration. The flaws were found to be at some depth and their magnitude was either less than 30% of the pile top impedance (a measure of pile size and/or concrete quality) or close to the shaft toe, if it was more than that. For example, Figure 3 shows a profile result having a 48% calculated impedance reduction at a distance of 7% of pile length above the shaft bottom. Considering that this reduction occurred just above hard rock where the temporary casing ended it is reasonable to assume that the shaft was of somewhat greater than nominal size above the very competent material and of reduced yet still sufficient size below that point. If such a change occurs gradually, then the Profile Method cannot detect it.

Three percent of the shafts initially indicated defects (PDx) either as being 10 to 15% shorter than planned or as having a major impedance reduction. In LST the accuracy of shaft length determination is made uncertain by the variability of the concrete wave speed, both with age and with type of concrete. Even at the same site and with concrete from the same supplier, variations in wave speed of 5% are common and an uncertainty of length determination of 5 or even 10% has to be expected. This uncertainty plus information about rock quality and installed concrete quality and quantity and rebar cage length, contained in the construction logs, supported the decision to accept the two potentially short shafts. Two other piles were classified as defective, indicating a major impedance reduction. However, due to the project’s time pressure, the tests had been conducted only three and four days after the concrete had been poured. It was decided to wait and repeat the tests after an additional waiting time of 6 days. The new records then showed a clear toe signal for a somewhat low, but reasonable wave speed of 12,200 ft/s (3,700 m/s) and what had looked like a defect could now be interpreted as a reduction following a major bulb supporting an AA classification.

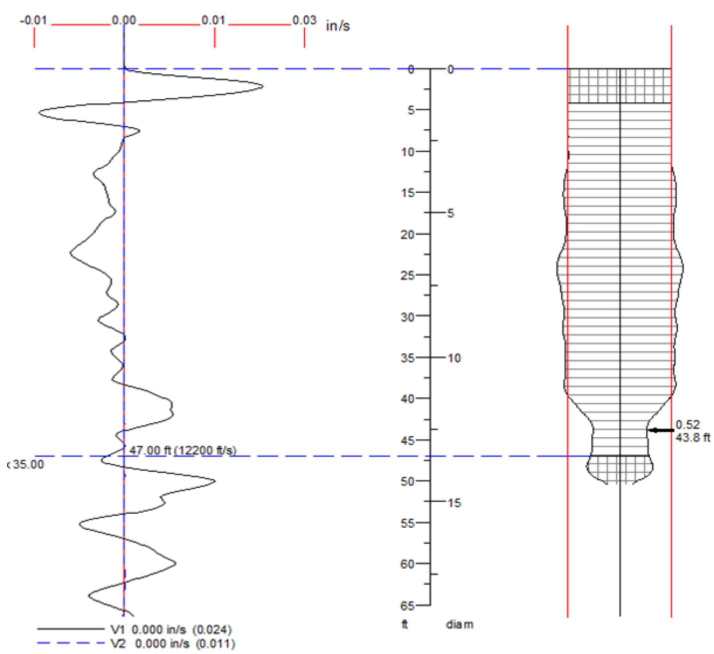

FIGURE 3 Low Strain Test Record and Profile Analysis Result (1 ft = .305 m).

SUMMARY AND CONCLUSIONS

In order to reduce the subjectivity from pile acceptance/rejection decisions after non-destructive testing has been conducted, record classification is highly recommended. The classifications presented in this paper have helped the test engineers and the recipients of the test report making sometimes difficult decisions.

Three of the four CSL examples discussed required mitigation in the form of coring, wash-out and grouting with retesting after the grout had hardened. The regrouted zones would not show the same CSL wave speed results of an intact concrete, however, such a lesser wave speed should be expected because of the unavoidable pulse reflections at the interface between grout and concrete and the differences in material properties. In one case, the quality of the shaft was assessed by dynamic load testing. In another example, the defective shaft was accepted as is, because an analysis showed that the affected bottom section was not critically needed for the required capacity.

The LST case study showed that the method can be challenging where high resistance, vibrating heavy reinforcement, and tight construction schedules lead to less than ideal test conditions. In such cases it is particularly important to properly classify the records and avoid rejecting piles when records are unclear yet do not contain characteristics typical of flaws or defects. In the example, most of the tested piles were found to be of good quality. In the few cases where flaws or defects were at first indicated, calculating the stresses at the defect location or waiting for concrete hardening solved the problems without further mitigation.

References

1. O'Neill, M., W. and Sarhan, H.A. Structural Resistance Factors for Drilled Shafts Considering Construction Flaws, *ASCE Geotechnical Special Publication No. 125*, Current Practices and Future Trends in Deep Foundations, J. DiMaggio and M. Hussein, ed., 2004, pp166-185.
2. Rausche, F. Non-Destructive Evaluation of Deep Foundations, CD ROM. Proceedings of the 5th International Conference on Case Histories in Geotechnical Engineering. New York, NY, 2004.
3. Mullins, G. Thermal Integrity of Drilled Shafts. Presentation to the Florida Suncoast Chapter, ACI, March 2008.
4. Likins, G., Rausche, F., Webster, K., and Klesney, A. Defect Analysis for CSL Testing, *ASCE Geotechnical Special Publication No. 158*, CD-ROM. Proceedings GeoDenver 2007, New Issues in Geotechnics, Denver, CO, 2007
5. Rausche, F., Likins, G., and Hussein, M. A Formalized Procedure for Quality Assessment of Cast-in-Place Shafts Using Sonic Pulse Echo Methods. Transportation Research Record Issue No. 1447. Design and Construction of Auger Cast Piles and Other Foundation Issues. 1994. Washington, D.C., pp 30-38.
6. Likins, G., and Rausche, F. Recent Advances and Proper Use of PDI Low Strain Pile Integrity Testing. Proceedings of the 6th Int. Conf. on the Application of Stress Wave Theory to Piles. Sao Paulo, Brazil, 2000; pp 211-218.