QUALITY ASSESSMENT PROCEDURE AND CLASSIFICATIONS OF CAST-IN-PLACE SHAFT USING LOW STRAIN DYNAMIC TEST

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Various nondestructive testing (NDT) inspection methods are available to evaluate the structural integrity of cast-in-place shafts. The widely used methods include Cross Hole Sonic Logging Testing and Low Strain Testing. Due to its advantages such as low cost, easy operation, quickness and flexibility (no need to plan ahead and prepare inspection tubes or other devices), Low Strain Test is frequently specified in quality assurance programs of many countries or when doubts arise as to the integrity of the finished shafts/piles. The method is well suited for small to middle sized shafts. However it is an indirect NDT testing method and has certain limitations. Data interpretation requires proper training, experience and judgment and, therefore, inconsistent conclusions and reporting may be provided by different testers. To avoid or reduce such inconsistencies, it is best to follow a standardized data interpretation and record classification system.

In this paper, a new classification method is presented with examples. A step-by-step data evaluation and interpretation procedure is proposed with examples of real cases to help understand the LST data. The paper also makes recommendations for measures to be taken when anomalies are detected in tested production piles.

INTRODUCTION

Cast-in-place piles such as augered-cast-in-place (ACIP) piles and drilled shafts are produced by drilling holes in the ground and filling them with concrete. Compared to driven piles, they may have advantages such as lower perceived vibration and noise. However, since direct inspection of the finished product is impossible, the final foundations often are questioned regarding their structural integrity. Integrity tests, excavated foundations as well as failed static tests have revealed cast-in-place piles with defects on numerous occasions (e.g., O'Neill and Sarhan, 2004). For this reason, concerned engineers and/or owners require as part of their quality assurance program that integrity testing be conducted either on a percentage or on a sample of randomly picked piles or on piles with an unusual construction history.

Various nondestructive testing (NDT) inspection methods are available to evaluate the structural integrity of cast-in-place piles. Widely used dynamic methods include Cross Hole Sonic Logging Testing (CSL), High Strain (HST) and Low Strain Testing (LST). Also a method based on temperature measurements during concrete curing enjoys increased acceptance due to its speed and more conclusive results (Mullins, 2008). However, due to its low cost, easy and quick operation and flexibility (no pre-preparation such as the installation of inspection tubes), LST is often specified in many different countries.

The LST method, the subject of this paper and in use since the 1970s, is standardized by ASTM D5882. It 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 positive velocity change (in the same direction as the impact pulse) 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 reduced concrete strength. LST exists in two forms:

1. Pulse Echo Method (PEM) which only requires measurement of the pile top velocity, and
2. Transient Response Method (TRM) which in addition requires measurement of the impact force.

The signals of velocity and optionally force can be analyzed both in either time or frequency domain. The procedure to analyze the data in the time domain is the same for both methods, i.e., examining the variation of velocity vs. time curve. This is common practice in the United States. The frequency analysis (Davis and Dunn, 1974) can be applied to either the velocity signals of the PEM alone or to both velocity and force signals. With TRM, the mobility is computed as the ratio of velocity and force. In either case the frequency difference Δf can be determined from subsequent peaks of the velocity or mobility spectra and converted to pile length, L = c/(2 Δf). TRM also allows for the calculation of a dynamic stiffness value which may be helpful for a relative pile quality evaluation. Information gained from TRM sometimes helps integrity assessments near the pile top or confirms the data interpretation by PEM (Figure 1).

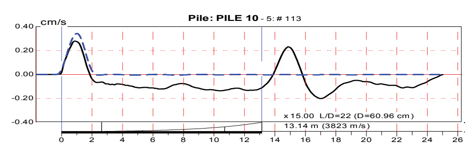
Data interpretation is not straight forward. Subsurface conditions, construction methods and difficult soil conditions or very large pile lengths create complexities such as highly non-uniform shafts, variable concrete qualities, large length over diameter ratios and related high wave energy dissipation due to friction. To aid in this process, the following presents a step-by-step data interpretation system and an associated record classification method. The following discussion will be limited to

- Pulse Echo Method (PEM),
- Quality assessment of newly constructed foundations with known constructed pile lengths,
- Concrete piles (steel piles and timber piles are less frequently tested by PEM)
- Sites where at least 5 comparable piles are tested.

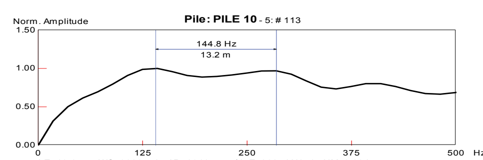
Definition of Terms

The following are terms and sign conventions used in this paper:

- Downward particle velocity is positive.
- A tension reflection wave (e.g., generated by a cross sectional reduction or the pile end) produces a positive pile top velocity increase;
- A compressive reflection wave (e.g., generated by a cross sectional increase) produces a negative pile top velocity increase;
- The pile impedance is equal to A (E ρ)$^{1/2}$, where E is elastic modulus, ρ is the mass density of the pile material and A is the shaft's cross sectional area. Impedance is, therefore, both a measure of the pile's size and concrete quality.
- The pile material wave speed is c = (E / ρ)$^{1/2}$.
- An anomaly is a deviation of the impedance from the nominal value. A defect or flaw is an impedance reduction. The depth below the pile top of an anomaly can be calculated from the time of reflection arrival at the top and the wave speed.
- A flaw is a lesser impedance reduction than a defect. Exact definitions are not possible.



(a)



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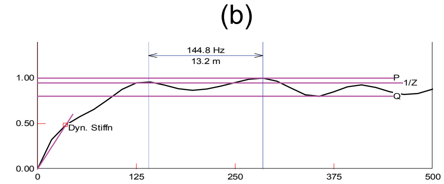


(c)

Figure 1. Example Record (ACIP; D=61 cm or 24 inch; L= 13.2 m or 43 ft): a) Time Domain Plot (Force dashed, velocity solid); b) Velocity Spectrum; c) Mobility

DATA ACQUISITION

Without high quality data, it is impossible to interpret data correctly. The background and the proper procedure to perform LST tests correctly has been discussed by Rausche, etc. (1994) and Likins and Rausche (2000). For example, it is important to collect records which are the average of 3 to 5 consistent signals. It is also important to perform multiple tests for each shaft with different sizes of hammers. Larger hammers induce wider impact pulses (lower frequency content) and higher energy, which help produce a clearer toe reflection. A small hammer induces higher frequency signals providing for a better resolution of anomalies near pile top. Acquisition of multiple records on the same shaft helps identify common features, removes spurious noise signals and shows consistency and quality of the data.

Before testing it is important to check the quality of the pile top concrete and its size just below the top. In particular, the test engineer has to make sure that contaminated concrete/grout is removed and the solid concrete/grout surface is ground smooth at a few spots for a clean impact and reliable sensor attachment.

The test engineer should check the pile size in the vicinity of the pile top. This is important, since the hammer impact generates a stress wave which, directly underneath the hammer, is very limited in horizontal extent. The test results (impedance changes) should therefore be seen in relation to the pile size some distance below the pile top. For example, a shaft with nominal top area, but significantly larger size within one diameter from the top, could lead to overestimations of anomalies when it is possible that the shaft reduces back to the nominal size at some distance below the increase.

SPECIFICATIONS

Low strain tests are often specified as part of quality assurance program for a new construction project and the specifications for LST should address or include the following items.

1) Testing procedure and equipment to be compliant with ASTM D5882 (or other local standard).
2) Number of test piles. (Depending on the type of deep foundation and/or the number of piles in the foundation, between 25 and 100% of all piles).
3) Replacement test (In a difficult testing environment, e.g. long , slender piles, a 25% percent testing specification would be reasonable with the requirement that inconclusive tests (see “I” categories below) be replaced with additional pile tests.)
4) Preconstruction tests (In a difficult test environment for a suitability check of LST, as per Rausche, et al., 2008.)
5) Experience (data interpretation by an engineer with at least 3 year experience and/or peer review.)
6) Pile acceptance or rejection (e.g., a decision tree showing measures to be taken in case a flaw or defect record is identified; see below for further discussion).

DATA INTERPRETATION

Like all indirect testing methods, LST has limitations and data interpretation is not necessarily simple and depends heavily on the clarity of the records and reflections which diminishes as soil resistance, pile non-uniformities and/or pile length increase. Sufficient training and experience of the test engineers can help reduce, but not completely eliminate, problem records. To help interpret data and the communication, the authors’ company originally proposed a 4-category classification system (Rausche, et al., 1994). This simple system lead to some confusion and allowed for ambiguities. Webster, et al. 2011, therefore, proposed an expanded system (see Table 1). Examples of application of this procedure are described below.

Step 1: Collect Additional Information

In addition to LST data, the following information will help with data interpretation and the pile acceptance/rejection process:

1. Pile installation record including
   a. Date of installation/curing age of concrete;
   b. Concrete mix design details including admixtures and design strength;
   c. Total installed concrete volume and nominal volume;
   d. Actually constructed pile length;
   e. Wet (water/slurry) or dry hole;
   f. Concrete casting details;
   g. Times of hole completion, beginning and finishing of concrete pouring;

   h. Interruptions of drilling and/or casting.
2. Planned cross-sectional variation;
3. Permanent and temporary casing diameters and lengths;
4. Testing condition at/near pile top: actual top area vs. nominal top near the pile top (say over a depth of 1 diameter);
5. Reinforcement details including length of rebar above pile top surface;
6. Soil information such as soil boring;
7. Drilling observations including speed of progress, soil types excavated and water table;
8. Observations about water movements in drilled hole.

Step 2: Preliminary processing

The following tasks are usually done at the time of field data acquisition, but in complex situations have to be repeated in the office.

1. Given the constructed pile length, find an approximate **wave speed**. If records of several piles have a clear wave return from the toe and the pile length is known, then an average wave speed is easily determined. If this is not possible the wave speed has to be determined by local experience and the strength and age of the concrete. If no experience exists, 4000 m/s (13,100 ft/s) is a good starting value.

2. Based on the assumed wave speed the records are displayed or plotted vs. time, t, but with a **length scale** based on the wave speed (x = t c/2). In the following, instead of time after impact, length or distance below pile top may be used in the discussion.

3. Energy losses due to soil resistance, pile non-uniformities and/or pile material damping reduce reflections from the lower pile portion. As a compensation for this signal reduction an **amplification**, exponentially increasing with time, is applied to the records which helps identify and measure reflections from the lower pile portion and the pile bottom. The exponential function is defined by starting time and amplitude. To prevent record distortions and misuse, an amplification starting time of 20% of the time required for the wave to travel twice along the pile length (2L/c) is recommended; under no circumstances should it exceed 50% of 2L/c. The amplification amplitude should be chosen such that the magnitude of reflections from the pile bottom is approximately equal to the input pulse. A magnification amplitude greater than 100 is not recommended. Also for piles of different lengths at the same site, the magnification functions should be chosen such that they produce the same multipliers at the same depths.

4. The quality and consistency of records can now be checked and, given more than one record for each hammer weight, one each **record is selected for data interpretation**. Obviously, the selected records should be the clearest ones available.

5. **Further data enhancements** are occasionally necessary, depending on the difficulties encountered at the site.

   a. High-pass filtering removes low frequency record components below a specified frequency f_{hi} which may cause a velocity drift. The source of such low frequency components may be soil resistance effects, pile top conditions etc. The filter frequency is often expressed as a wave length $HI = c/f_{hi}$. Using too small a HI (too low a filter frequency), the high-pass filter may remove or alter important record characteristics. In general, high-pass filtering is discouraged.

   As an example, consider the unfiltered LST record of Figure 2a, taken on a 750 mm (30 inch) diameter ACIP pile of 15 m (49 ft) length. A high (250 Hz or 15 m wave length) high-pass filter frequency has been applied to the record in Figure 2c (removing record components of less than 250 Hz frequency); Figure 2b shows the same record after applying a more reasonable filter frequency of 20 Hz (200 m). In Figure 2a, a reference line was drawn establishing a low frequency drift (in this case due to soil resistance). In Figure 2c, the horizontal axis is used as reference line. The area between reference line and processed signals has been marked with a hatch pattern. The area below (above) the reference line is interpreted as an impedance increase (decrease). Comparing both areas it is concluded that the pile has a bulge which begins near 6 m and ends near 9 m depth. Since in Figure 2a the two areas approximately match each other it can be concluded that pile has the same impedance below the bulge that it had above the bulge. If, however, the curve of Figure 2c were interpreted, the erroneous conclusion would be made that the pile is severely defective.

b. Low-pass filtering, by wavelet or time averaging methods, removes high frequency components. High frequency noise eliminated by low-pass filtering may be caused by electronic interference, mechanical noise, micro cracks near the top, etc. It is important to identify the source since it is easy to confuse noise with defect signals. High frequency noise due to mechanical effects can be avoided by careful pile top preparation including bending away free reinforcement bars extending above the pile top surface and trying different hammers. While high-pass filters should cautiously be applied with a low cut-off frequency (large wave length), low-pass filters should be used with a high cut-off frequency (low wave length).

Step 3: Finding Average Wave Speed

The processed records must again be inspected for clear toe signals and their wave speeds can now be more accurately determined. As shown in Figure 1a, two vertical lines are used as markers, the first vertical dash line is plotted at the beginning of the rise time of the input pulse and the second vertical dash line is plotted where the reflection pulse begins (after time 2L/c with L being the length from accelerometer to pile toe). The location of second vertical dash line is affected by the wave speed used for interpretation. The wave speed should be determined by positioning the second vertical dash line just at the beginning of the rise time of the observed toe reflection. After tabulating all wave speeds determined in this manner, an average wave speed, c_{avg}, is calculated which includes only values within 5% of the average.

Note: when deciding on a pile toe reflection, care should be taken not to erroneously identify a secondary reflection from an earlier impedance change.

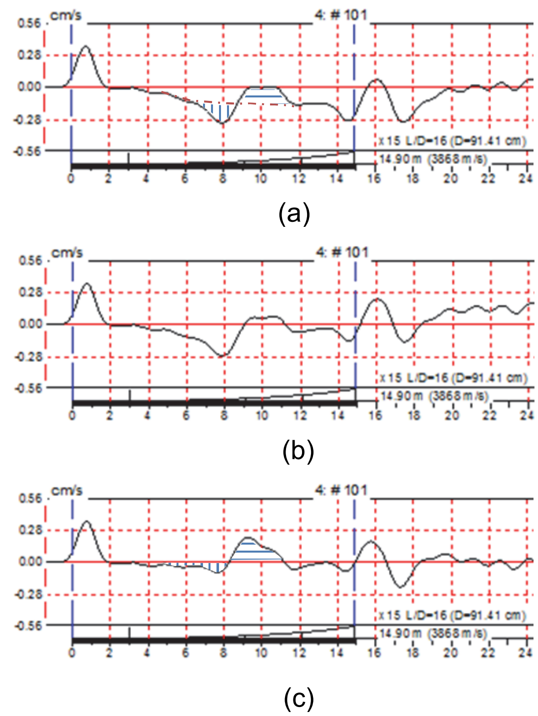


Figure 2. Example of Improper Use of High-Pass Filtering (ACIP Pile: Augured diameter = 750 mm or 30 inch): a) Without HI; b) HI = 200 m; c) HI = 15 m

Step 4: Assigning Record Categories

Categories are listed and explained with commentary and record examples in Table 1.

The shafts with records showing a clear toe reflection fall in either the AA or PF category. The following rules may be used to distinguish them:

- AA (sound shaft integrity indicated) is for the records with minor velocity variations before a toe reflection as shown in Figure 1 and with a wave speeds within 5% of c_{avg}. The 5% window is a frequently recommended value. Local experiences with a greater variability of wave speeds may dictate a wider acceptance limit which, however, should not be greater than 10%. AA records are also those which have either only negative reflection pulses or where a negative pulse precedes a positive one with similar or greater pulse areas. (See examples in Figures 2a and 3b).
- AB records have no toe signal but do not suggest an anomaly either. In these cases it is often possible to determine a depth, x,

to which the record gives a clear indication of neither a flaw nor a defect. This depth x may be known from site experience (i.e., records of other piles) or from the generally accepted rule of thumb which states that the pulse echo method can check the pile to a depth of at least 30 pile diameters. Sometimes AB records are caused by high soil resistance and may therefore indicate that the pile can carry higher loads than an AA pile. However, under no circumstance can LST allow for soil resistance assessments. A heavier hammer or a hammer capable of inducing high energy low frequency content can be used to improve the tests.

- PF (Potential flaw) records show one or more positive velocity reflections not preceded by negative ones of nearly the same or greater area. They indicate at least one impedance reduction. However, since a toe signal is apparent the reduction is not as severe as a defect which would be of such a magnitude that it blocks the impact wave from reaching the toe or the toe reflection from reaching the top. Quantification of the flaw should be attempted, by either Profile Analysis (see Figures 3 and 4) or other numerical method. For PF the depth x where the flaw exists should be determined since it may be helpful in deciding whether or not enough load shedding has taken place above the flaw for sufficient pile structural strength at the flaw location.
- PD (Potential defect) records require that further efforts be taken to assure that the shaft is not seriously defective. PD records have no toe signal within 5% (or 10% if that is acceptable at the specific site) of the expected time. These records may take on one of at least three different forms (Figure 5):
  1. One or more positive pulses not preceded by negative ones of nearly the same or greater area. (Note that defects close to the top often generate secondary signals (Figure 5c) which should not be confused with additional anomalies).
  2. An unusually wide input pulse, indicating that the defect is close to the top.
  3. An early toe signal suggesting a pile length of less than 95% (90% if a 10% wave speed variation is acceptable) of constructed length (alternatively indicating a wave speed greater than 105% (110%) of c_{avg}.). Examples are shown in Figures 5a and 5b.

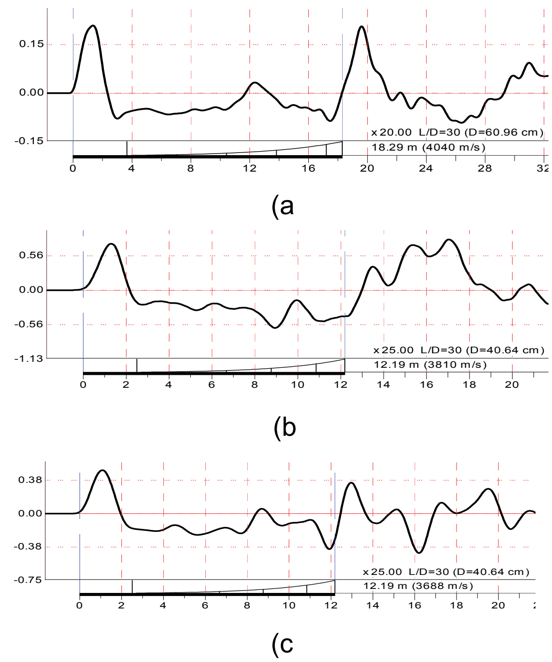
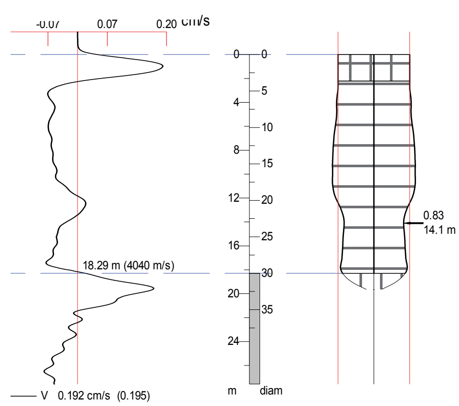
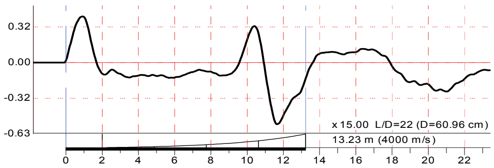


Figure 3. Examples of ACIP records (a) D=610 mm (24 inch) and L=18.3 m (60 ft); PF category, reduction beginning at 10 m; (b) D=406 mm (16 inch) and L=12.2 m (40 ft); AA category with bulge beginning at 8 m; (c) Pile as in (b) but PF category with impedance reduction beginning at 8 m.



(a) (b)

Figure 4. Profile Analysis for Record shown in Figure 3a: a) pile top velocity vs. time (downwards); b) estimated impedance profile indicating an estimated 17% reduction relative to pile top impedance.



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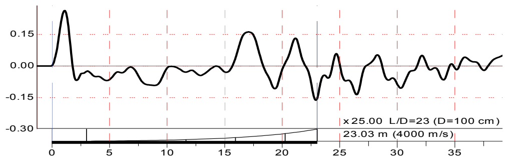

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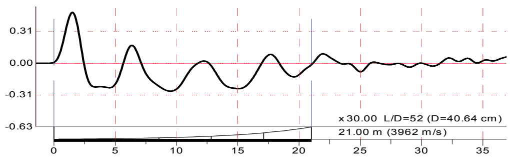

(c)

Figure 5. Examples of PD Category Records with significant positive reflections (SPR) assuming consistent magnification with other records at the same site: (a) No negative reflection before SPR at 9 m; (b) SPR near 15 m and only a small negative reflection (at 7 to 10 m); (c) SPR starting at 5 m followed by secondary reflections.

To avoid assigning erroneously the PD category, consideration should be given to the following.

- If by comparison with records of non-PD piles (same magnification for the same depth) it is found that the positive pulses (are of minor magnitude) then PF maybe assigned.
- If other similarly constructed piles have Category AB (no defect and no toe signal), then PF may be assigned, unless the positive reflection is so large that it indicates a short pile.

- IR and IV records are either too complex or at least partially unclear as explained in Table 1. Retesting sometimes leads to better results. Testing instead another pile may be a possibility unless specifications call for 100% pile testing. In that case, after the questionable piles have been retested (or at least 10% of all piles) with little success, the specifications should recognize the limitations of the method.

False Diagnoses of Flaws or Defects

The following is a list of unusual circumstances which can give false indications of flaws or defects:

1. Splices or cold joints (concrete poured after interruptions)
2. Horizontal shrinkage cracks in pile (may occur in the absence of reinforcement)
3. Gradually or very strongly increasing shaft size and then sudden reduction to nominal.
4. A very stiff soil layer over a very soft one.

Recommendations for Further Action

It is not recommended to use LST as the sole method for pile rejection or acceptance.

Piles falling under the AA or AB categories need no further testing.

Piles with PF records

i. Should be compared with soil profiles, drilling logs and/or other installation records and with LST records of other piles at the same site; consistent record features may suggest acceptable pile or record characteristics.
ii. Should be further analyzed (e.g., Profile Analysis) to quantify the potential flaw. If the flaw is at a depth where loads are sufficiently reduced then the pile maybe acceptable.

Piles with PD records

i. First do the review stipulated under (i) in PF
ii. Check if a short pile would be sufficient to carry load
iii. Check if a replacement pile would be more cost effective than other measures
iv. Consider excavating for shallow defects
v. Consider drilling through concrete, washout and pressure injection.
vi. Consider accepting pile after (dynamic) load testing

Piles with IR or IV records

i. Repeat test after improving pile top condition
ii. Instead test another pile (specifications may allow for a certain number of replacement tests)

Example

LST tests were requested for 108 ACIP piles of 610 mm (24 inches) diameter and 18 m (60 ft) length at a construction site for an industrial plant. An average wave speed of 4,010 m/s (13,150 ft/s) was determined with a minmum of 3,810 m/s (12,500 ft/s) and a maximum of 4,270 m/s (14,000 ft/s). Except for one pile, having a calculated wave speed 6.5% higher than average, the calculated wave speeds fell in a ±5% window of the average and most of these records were categorized as AA. Profile analysis were performed for four shafts, classified as PF; one of these records and the corresponding analysis result are shown in Figure 3a and Figure 4.

Pile top concrete was of good quality after being well prepared for testing; three different hammer weights were used for data collection on each pile. As a result all records were conclusive (No IV or IR records).

However, negative reflections (impedance increases), considered site characteristic features, occurring between 2 and 4 m depth sometimes blocked the toe signal. Thus 20 piles had to be categorized as AB.

One pile was identified as PD due to an early toe signal.

SUMMARY AND CONCLUSIONS

In order to reduce the subjectivity of pile acceptance/rejection decisions after LST has been conducted, record classification using the system proposed by Webster, et al. (2011) and shown in Table 1, is highly recommended.

When specifying LST, it has to be recognized that not all test may produce conclusive results. These records may be falling in categories AB, IR and IV.

The occurrence of inconclusive records can be reduced by careful pile top preparation and by working with different hammer sizes and weights.

Proper data interpretation requires experience and training. Where this is not available a peer review of the report is highly recommended.

QA specifications calling for LST should also outline measures, such as those described above as “Recommendations for Further Action”, to be taken for piles in categories other than AA or AB.

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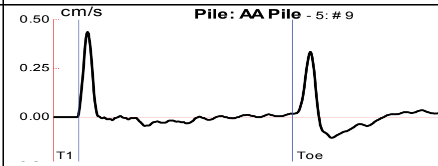
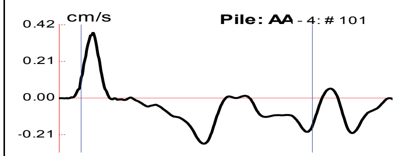
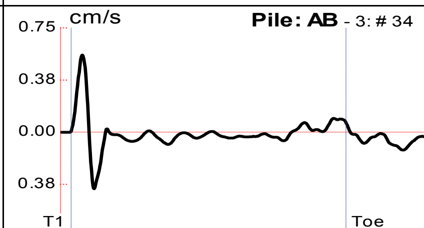
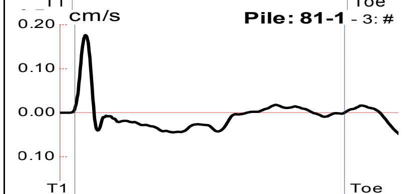
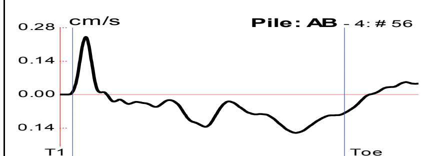
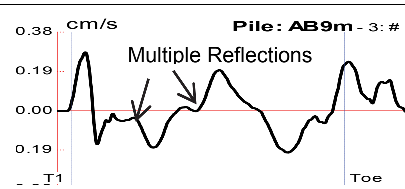
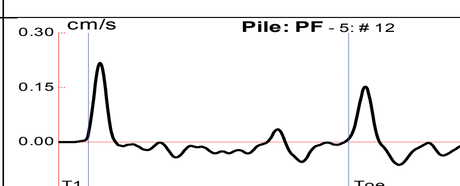
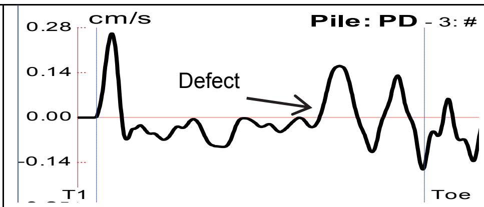
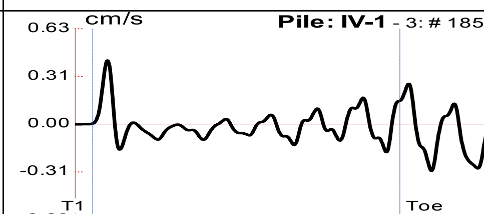
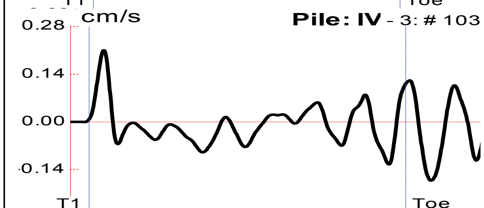
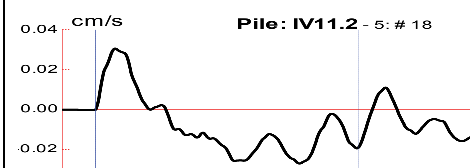
Table 1. Recommended LST Records Classification for Concrete Pile Integrity

Class	Class Name	Commentary	Examples of Records
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. Note that LST cannot provide information as to soil resistance; however, an unusually high toe signal may be caused by a low end bearing.	 
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 without flaw or defect 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.