Recommendations on Two Acceleration Measurements with Low Strain Integrity Test

Liqun Liang, PhD., P.E.,[1] Scott Webster, P.E.,[2] and Marty Bixler, P.E.[3]

[1]Pile Dynamics Inc., 30725 Aurora Rd, Cleveland, Ohio 44139; e-mail: lliang@pile.com
[2]GRL Engineers Inc., 30725 Aurora Rd, Cleveland, Ohio 44139; e-mail: SWebster@grlengineers.com
[3]GRL Engineers Inc., 30725 Aurora Rd, Cleveland, Ohio 44139; e-mail: MBixler@grlengineers.com

ABSTRACT

As more existing structures need to be reevaluated, repaired or expanded, the demand of use of a Low Strain Integrity Testing (LST) to determine/corroborate the existing pile/shaft length and integrity under existing structures has also increased. When applying LST to the piles under existing structures, multiple downward travelling waves will superpose with the upward traveling waves (reflection from defects and the toe). This makes the data interpretation very difficult when only one acceleration measurement is obtained. Two acceleration measurements were introduced about twenty years ago as an extension to LST and significantly improve the reliability of application of LST to piles under existing structures. However, due to the complexity of testing conditions, lack of clear guidelines and experience, this technique has not been frequently applied. After discussing the background of this method, this paper presents case studies and recommendations on the application of this technique.

INTRODUCTION

Various nondestructive testing (NDT) inspection methods are available to evaluate the structural integrity of cast-in-place shafts. Widely used dynamic methods include Cross Hole Sonic Logging Testing (CSL), High Strain (HST) and Low Strain Integrity Testing (LST) (Likins, and Rausche, 2000, Rausche et al, 2008, Webster et al, 2011, Liang and Rausche, 2011). 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 operation, quickness and flexibility (no pre-preparation such as the installation of inspection tubes), LST is often specified in many different countries for quality assurance. LST is also used to determine the integrity of preformed piles such as concrete or timber piles. As there is an increasing use of existing piles such as for cellular towers, reconfiguring, repairing or expanding existing structures, the demand for the evaluation of the integrity and length of piles under existing structures has significantly increased. Both LST and parallel seismic methods are used for these purposes. However, the parallel seismic method is limited to evaluate pile length only, and is not further discussed here.

The LST method, in use since the 1970s, is standardized by ASTM 5882. Traditionally, it primarily relies on the measurement of the pile top acceleration as the result of a light hammer impact. The measured accelerations are usually converted to velocity for interpretation in the time domain. Stress wave reflections from increases or decreases in shape or material quality (i.e., impedance change) along the pile are registered by the pile top measurements 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.

The LST can be applied to piles under existing structures where the pile top is incorporated in the superstructure and the pile length is unknown. However, two complications need to be addressed for proper evaluation of the velocity records: 1) The wave speed of pile material such as concrete or timber is not always known, which is an important variable affecting the accuracy of pile length determination; 2) For piles tested below their head (when they are incorporated in a structure), stress waves not only travel downward but also upward where they are reflected by the structure, pile top or non-uniformities. These secondary reflections traveling down from above the velocity measurement location have to be identified so as not to be confused with upward traveling reflections from pile impedance changes below the velocity measurement location or the pile toe. For this reason, Johnson and Rausche (1996), presented a new method by taking two acceleration signals simultaneously along the pile shaft that provide a means of determining the stress wave speed as well as the necessary information for separating downward from upward traveling waves. Since the method and the related analyses have been implemented in some devices and software in early 2000, its application has gained popularity. However, due to the complexity of the application, difficulties have been experienced both in testing and analysis due to lack of guidance and experience. In this paper, the background and principals are presented and a real test pile is used to verify the method and gain better understanding. A case study is then presented to demonstrate the applicability. Finally a comprehensive recommendation is presented to help guide future application.

BACKGROUND

Figure 1 demonstrates the stress wave traveling paths for a simple case when acceleration signals are taken at two locations along a uniform pile with a length of L and wave speed of the pile material of c. The first accelerometer labeled as A_1 is mounted along the pile at a distance of Z_1 with reference to pile top and the second accelerometer labeled as A_2 is mounted along the pile at a distance of Z_2 with reference to pile top. The absolute reference (pile top for this case) is not of importance, but both accelerometers must use the same reference, so the distance between them can be calculated. When a hammer impact is applied at the pile top, a downward travelling wave reaches A_1 first at time t_1, then A_2 at time t_2. When the stress wave reaches the pile bottom at time of L/c, the stress wave is reflected to become an upward travelling wave. The upward traveling wave will reach A_2 first at time t_3, then A_1 at t_4. Finally, at the time of 2L/c, the upward traveling wave will arrive at the pile top. Let's define:

- Distance between A_1 and A_2: $D = Z_2 - Z_1$
- Time for wave travel between A_1 and A_2: $T = D/c$

And we have following relationships:

- $t_1 = Z_1/c$; $t_2 = Z_2/c$; $t_2 = t_1 + T$
- $t_3 = t_2 + 2*(L - Z_2)/c$; $t_4 = t_1 + 2*(L - Z_1)/c$; $t_4 = t_3 + T$

For interpretation purposes, the measured accelerations are integrated to velocity and the resulting V_1 and V_2 velocities are computed from the accelerations measured by A_1 and A_2 respectively. V_1 and V_2 are the pile particle velocities registered at the accelerometer locations and include both components from downward and upward travelling waves. For this simple illustration case, V_1 and V_2 only include components from the downward traveling wave before the t_3 time because of 1) a uniform pile; 2) no resistance forces acting on the pile, i.e., no wave reflection prior to reaching the pile toe; 3) impact applied at pile top. At time t_3, V_2 will only include components from the upward traveling wave and at time t_4, V_1 will only include the components from the upward traveling wave. For a more complicated (and realistic) case, V_1 and V_2 may include components from both downward and upward travelling waves from impedance change (including toe) reflections. Upward travelling stress waves include the most meaningful information since they are reflected from pile impedance changes including defects and pile toe and soil resistance, so it is important to separate velocities into downward traveling and upward traveling waves. With two acceleration measurements, the velocity at A_1 location from the **downward** traveling stress wave can be computed by (Johnson, M., and Rausche, F., 1996):

$$V_1{\downarrow}(t) = V_1(t) - V_2(t-T) + V_1{\downarrow}(t-2T) \qquad (1)$$

Where:

$V_1{\downarrow}(t)$ – velocity component from downward travelling stress wave at time t, computed for A_1 location

$V_1(t)$ – velocity including components from both downward and upward travelling stress waves at time t, measured by A_1

$V_2(t)$ – velocity including components from both downward and upward travelling stress waves at time t, measured by A_2

Now the velocity at A_1 location from the **upward** traveling stress wave can be computed by:

$$V_1\uparrow(t) = V_1(t) - V_1\downarrow(t) \qquad (2)$$

Where:

$V_1\uparrow(t)$ – velocity component from upward travelling stress wave at time t, computed for A_1 location.

Figure 2a illustrates a more complicated case: a pile with a defect and also an effective impedance change at the bottom of the pile cap. One accelerometer A_1 is attached at the side of the pile at a distance Z_1 below the top of pile cap and above the defect location. A hammer impact is applied near the pile axis at top of the pile cap to induce a stress wave traveling downward. When this wave reaches the bottom of the cap, it separates into two waves due to the impedance change: 1) Part of the wave is reflected, which travels upward, defined as Stress Wave 1 (SW1); 2) The rest of the initially traveling downward wave continues to travel downward defined as Stress Wave 2 (SW2) and reaches A_1 as shown as pulse #1 recorded by A_1. Now the stress pulses observed at A_1 from SW1 and SW2 (ignoring tertiary reflections) are:

1. Part of initial impact stress wave (SW2): downward traveling;
2. Reflection from top of pile cap of SW1: now downward traveling;
3. Reflection from the defect of SW2: upward travelling;
4. Probably very small secondary reflection from top of pile cap of SW1: downward traveling;
5. Reflection from pile toe of SW2: upward traveling

The pulses observed at A_1 (1, 2, ..5) include both downward and upward traveling waves. However, only #3 and #5 are of primary interest since #3 includes the information of the location and extent of the defect and #5 indicates the location of the toe. If there is only one accelerometer used (the wave recorded at A_1 location), the data will show the result of all five waves superimposed, and it is impossible to tell which is from the important upward traveling waves. If another measurement is taken at A_2 location somewhere between A_1 and the defect location, equations (1) and (2) can be used to remove the downward traveling wave components from the A_1 data as shown in Figure 2b.

TEST PILE STUDY

To further verify and demonstrate the method, a concrete test pile was created as follows:

- Total Length: 12.2 m (40 ft)
- Cross section area: Square 254x254 mm (10x10 inch)

- An indent with depth of 75 mm (3 inch) between 3.05 and 3.96 m (10 and 13 ft) from pile top
- Concrete specific weight: 2400 kg/m^3 (150 pcf)
- Wave speed: 3800 m/s (12500 ft/s)

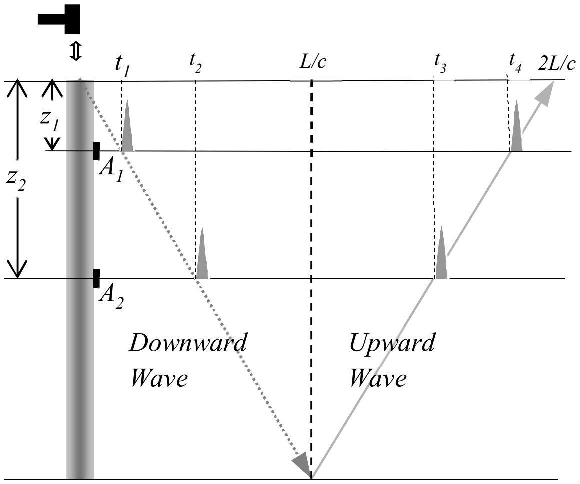


Figure 1. Illustration of the two accelerometer measurement: gage locations and wave propagation

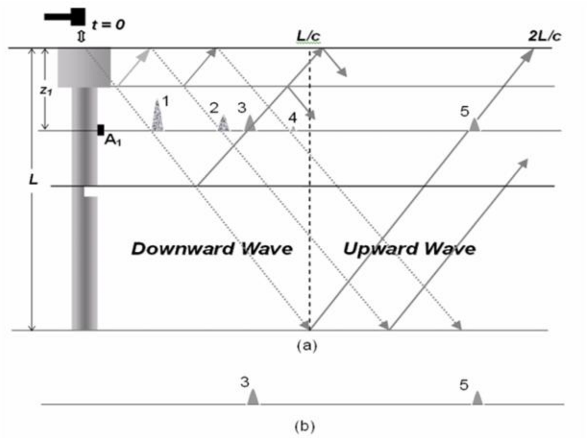


Figure 2. Illustration of a pile with a defect and hammer impact applied above the pile cap: a) all waves observed at A_1 including both downward and upward traveling waves; b) Only the wave components from upward traveling waves

The pile was laid horizontally on the ground to minimize soil resistance effects. As shown in Figure 3, two accelerometers, A_1 and A_2, were side mounted at 4.57 m (15 ft) and 5.18 m (17 ft) respectively. A hammer impact was applied at the bottom of the indent (3.96 m or 13 ft) to simulate testing under an existing structure. The impact generates stress waves travelling upward and downward and the paths of the stress waves are illustrated in Figure 3. Please note that only reflections from the pile top and toe are included in Figure 3, while the reflections that are relatively small from impedance changes along the pile are ignored for simplicity. In Figure 3, the dotted lines represent paths of the stress wave initially traveling downward from the impact location called "SW2" while the solid lines represent paths of the stress wave initially traveling upward from impact location called "SW1". Here is the list of the velocity variations observed at A_1 (the waves are numbered as labeled in the Figure 3):

1. Impact pulse of SW2
2. Reflection from pile top of SW1
3. Reflection from pile toe of SW2
4. Reflection from pile toe of SW1
5. Reflection from pile top of SW2

6. Reflection from pile top of SW1
7. Reflection from pile toe of SW2

The waves #3, #4 and #7 recorded at A_1 are reflections from the pile toe, which are upward traveling and of interest. Now let's look at the velocity measured at A_1 as shown in Figure 4. All of waves both from upward and downward traveling waves appear on the recorded A_1 data. Please note that #4 and #5 are superposed together due to the relatively wide input pulse. Except for the first pulse which may be easily judged as the initial impact pulse and a downward travelling wave, the other waves are impossible to tell if they is from downward traveling waves (reflected from pile top) or from upward traveling waves (reflected from pile toe).

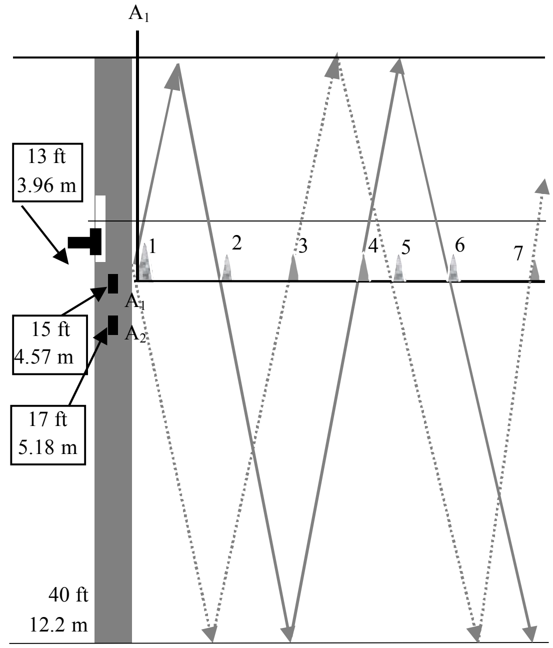


Figure 3. Lay out of test pile, gage location and wave traveling (The reflections from impedance changes at indent edges are ignored)

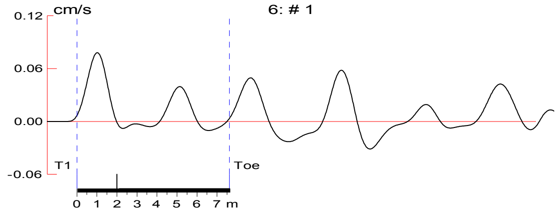
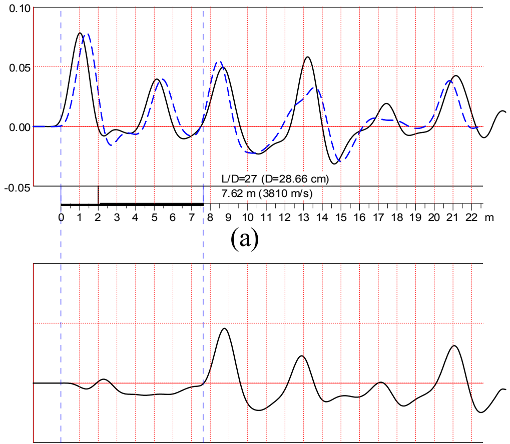


Figure 4. Test pile results: Velocity measured at A_1



(a)

(b)

Figure 5. Test pile: a) Velocity records at A_1 and A_2; b) Upward traveling velocity curve after two velocity analysis to remove downward traveling waves.

Both velocity records collected at A_1 and A_2 are shown in Figure 5a and the two velocity analysis was performed using equations 1) and 2) to remove downward traveling waves as shown in Figure 5b, which shows the reflections from the toe under A_2 clearly and makes the data interpretation easier. If the data quality is not good enough to perform two velocity analysis to obtain the result shown in Figure 5b, manual examination of two velocity curves may be needed (to look at phase shifts and determine the upward waves). If the wave travels down, the dark solid line from A_1 is ahead of the blue dotted line from A_2. Otherwise the wave is from the upward traveling waves.

CHALLENGES IN APPLICATION

The signals measured from the test pile are clean since it is under ideal conditions, and this helps to make the two velocity analysis easier. In reality, the signals taken from a pile under a more complicated situation may make interpretation more difficult. The following factors affect the quality of measured data:

- Non uniform pile;
- Complicated existing structures attached to pile;
- Effect of soil resistance;
- Effect of three dimensions due to:
    - Gages can only be mounted on the side;
    - Choices of impact location and direction are limited.

CASE STUDY

In this study, the testing data from the LST measurement for the FDOT Bridge No. 720060- SR 105 over Clapboard Creek, Duval County, Florida were used. The main testing objective was the assessment of the unknown in-place lengths of the 18-inch square concrete piles in-service supporting the bridge as shown in Figure 6. Data acquisition was done with a Pile Integrity Tester. Testing was performed by applying hand-held hammer impacts to the top of the pile cap concentrically over the top of each tested pile. Pile motion measurements were obtained with two accelerometers affixed at two locations along the pile lengths (Figure 6); locations are between 0 to 2.1 m (0 to 7 ft) as the axial pile distance below the bottom of the pile cap. The distances between two accelerometers were between 0.3 and 1.5 m (1 and 5 ft). Four sizes of hammers were used with weights approximately between 4.5 to 62.3 N (1 to 14 lb). For this project the main purpose to use two acceleration measurements was to distinguish the wave traveling direction rather than wave speed determination since there is a reasonable knowledge of wave speed for this type of pile, so the distance between two accelerometers was kept less than or equal to 1.5 m (5 ft). To determine wave speed accurately, it is recommended to place two accelerometers as far apart as possible and apply the highest sampling frequency. Several measurements taken with two accelerometers placed 1.5 m (5 ft) apart were used to check the wave speed used in the analyses.

The collected data, in form of velocity from both accelerometers, computed upward traveling velocity and wave traveling path for selected records from different piles are displayed in Figures 7 to 13. The layout of each figure is: top left - velocity curves from both accelerometers; bottom left - computed upward traveling velocity; right - wave traveling paths. For the selected records, the pile lengths determined varied between 18.3 and 20.1 m (60 and 66 ft) with wave speeds varying between 3900 and 4200 m/s (12800 and 13800 ft/s). A typical wave speed for concrete pile is 4000 m/s (13000 ft/s). For prestressed concrete piles, it might be higher. A variation of wave speed in one job site within ±5% may be expected, so the estimated pile length may have an error of ±5%. In this study, the wave speed was varied to match the observed toe reflection time to a reasonable pile length. It can be seen that clear toe reflections were observed from the computed upward traveling velocity plots (bottom left).

Figure 6. Photos of the Bridge, Bents, Pile and Locations of Accelerometers

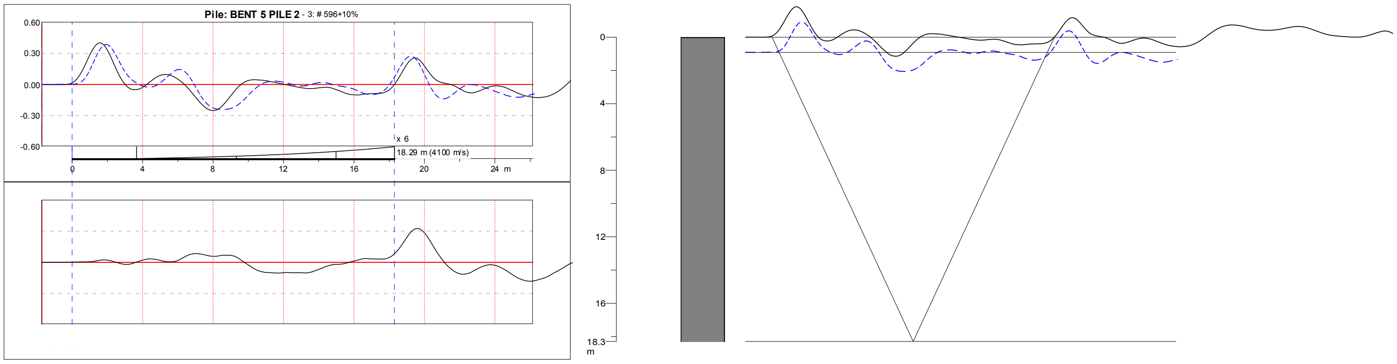


Figure 7. Bent 5 Pile 2: A_1 at 0.3 m (1 ft) and A_2 at 1.37m (4.5 ft)

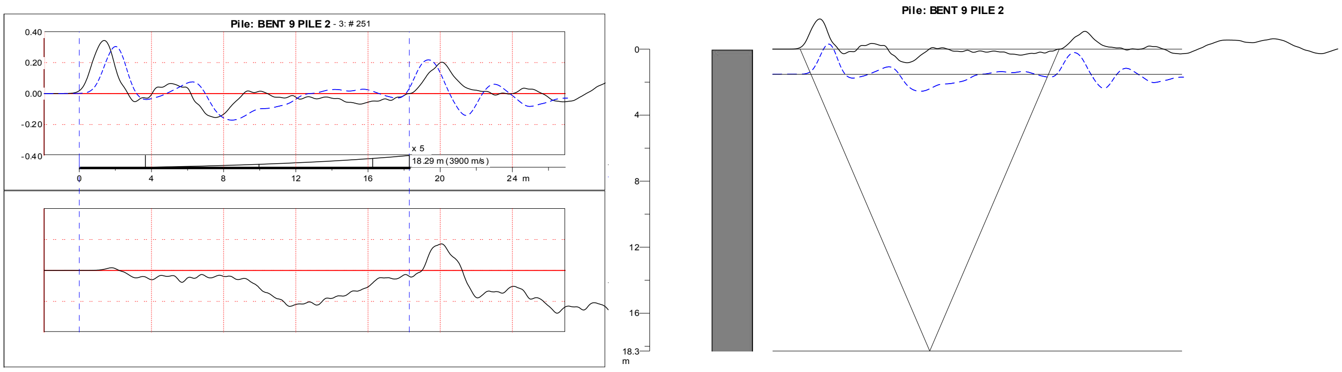


Figure 8. Bent 9, Pile 2: A_1 at 0.6 m (2 ft) and A_2 at 2.1m (7 ft)

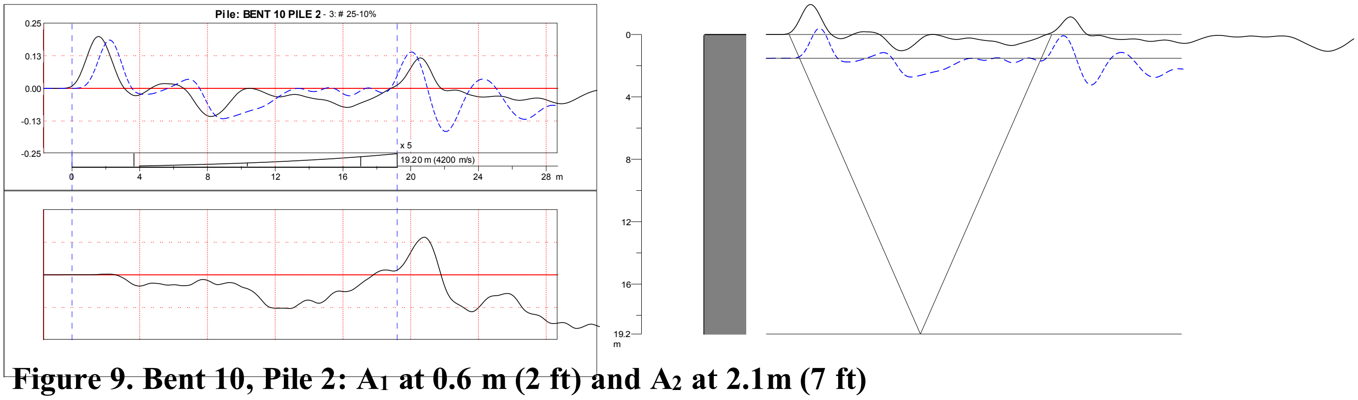


Figure 9. Bent 10, Pile 2: A_1 at 0.6 m (2 ft) and A_2 at 2.1m (7 ft)

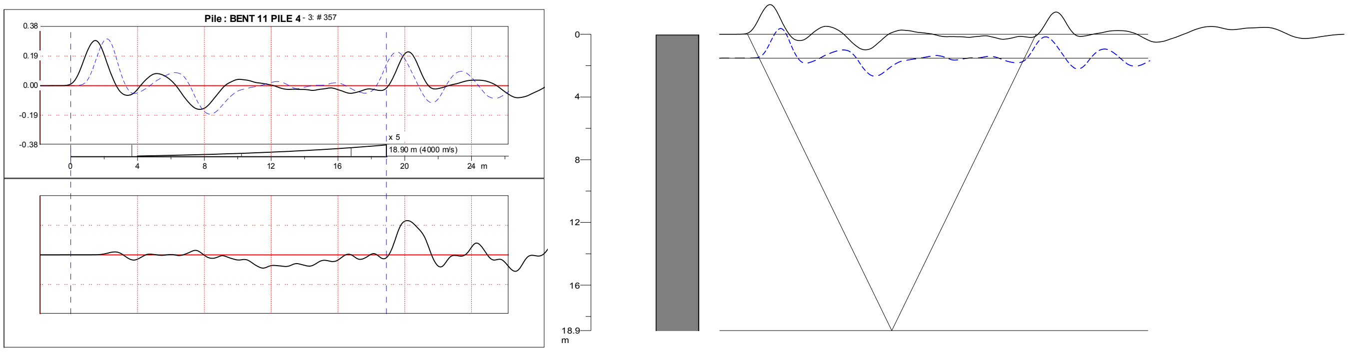


Figure 10. Bent 11, Pile 4: A_1 at 0.6 m (2 ft) and A_2 at 2.1m (7 ft)

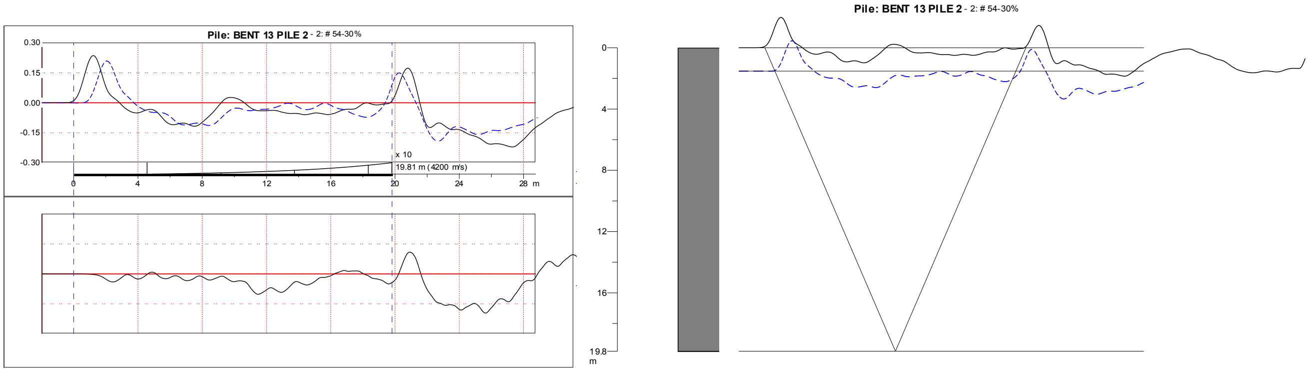


Figure 11. Bent 13, Pile 2: A_1 at 0 m (0 ft) and A_2 at 1.5 m (5 ft)

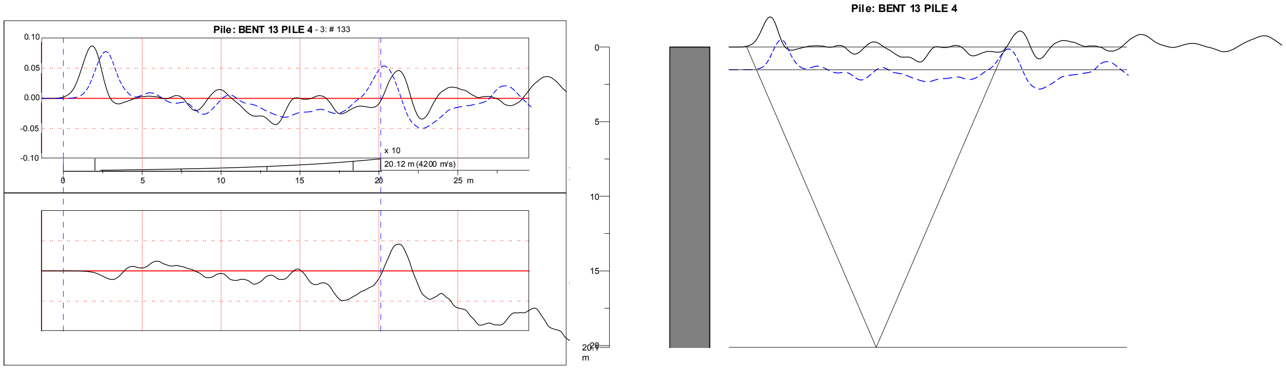


Figure 12. Bent 13, Pile 4: A_1 at 0 m (0 ft) and A_2 at 1.5 m (5 ft)

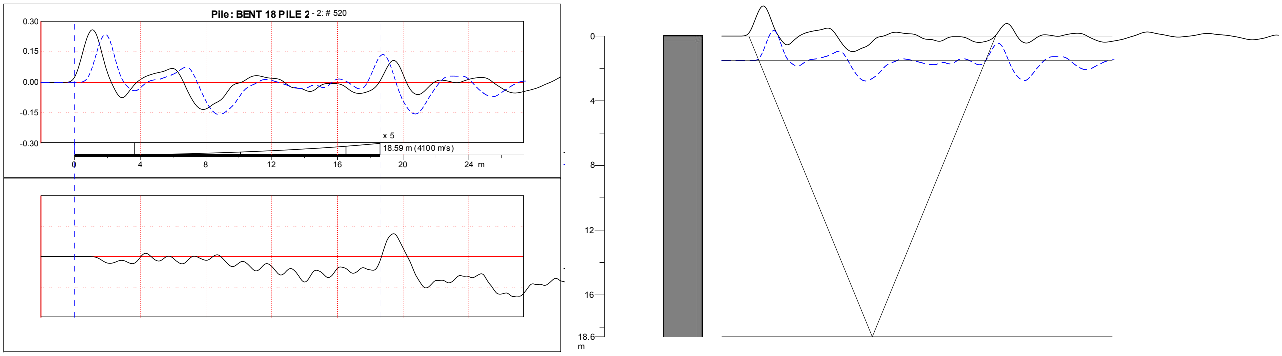


Figure 13. Bent 18, Pile 2: A_1 at 0.6 m (2 ft) and A_2 at 2.13 m (7 ft); Middle Size Hammer (8 lb)

For Pile #2 in Bent #18 (Figure 13), the results from different sizes of hammers (1 lb and 14 lb) are shown in Figure 14 and Figure 15. Small hammers (or hard impact tip) generate higher frequency input which helps identification of defects near pile top. However, the higher frequency content sometimes is more susceptible to show existing structure interference making the data analysis more difficult as shown in Figure 14. If this data has to be used to interpret results, then manual examination has to be performed. Let's look at the pulse P from A_1 starting around 4 m (fifth pulse) and the corresponding pulse arriving at A_2 as P' since P' is the fifth pulse on A_2 (the blue dash curve). An additional check to make sure that P and P' are the same pulse is that the distance between them is nearly the same as the distance between the first pulses on A_1 and A_2. Since P' is behind P, this pulse is part of the traveling downward wave. The right plot of Figure 14 shows the reflection paths as red dash lines. If P is part of the reflection (upward traveling wave), P and P' would be on same path, but they are clearly not. Thus the wave pulse P is not a reflection from a defect or the pile toe.

A larger hammer or softer tip generates lower frequency content (Figure 15) which often results in a clearer interpretation of the toe reflection, and the wide input pulse helps reduce or filter out noise. The drawback is that the lower resolution may result in the loss of detection of small defects or defects very near the pile top. Therefore it is recommended to use multiple sizes of hammers. For this project, the 8 lb hammer used gave the most reasonable data quality, adequate resolution and enough energy to see the toe reflection.

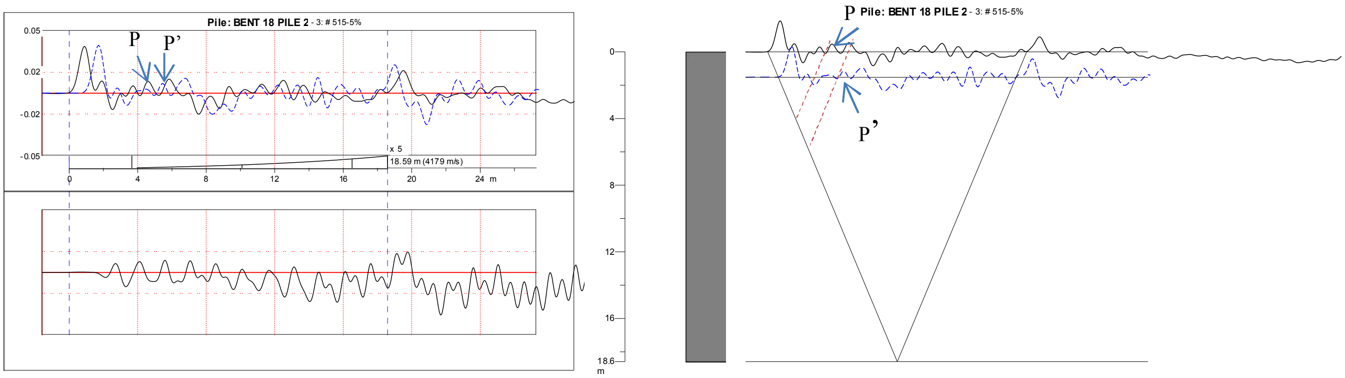


Figure 14. Bent 18, Pile 2: A_1 at 0.6 m (2 ft) and A_2 at 2.13 m (7 ft); Smaller Hammer (1 lb)

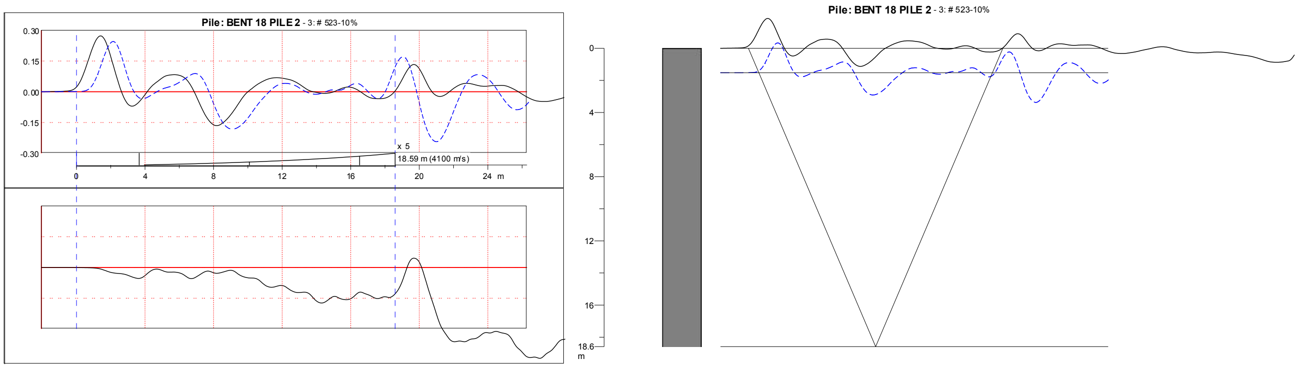


Figure 15. Bent 18, Pile 2: A_1 at 0.6 m (2 ft) and A_2 at 2.13 m (7 ft); Larger Hammer (14 lb)

RECOMMENDATIONS

Due to the difficulties of the application as discussed above, it is important to take a correct approach to use this method to obtain a reasonable result. The following are the recommendations based on our experience of applications and studies.

Accelerometer Mounting

Two accelerometers, A_1 and A_2, are installed along the pile at depths Z_1 and Z_2 which should be measured from same reference. It is important to accurately measure the distance between A_1 and A_2. Accelerations resulting from an impact applied somewhere above A_1 are recorded by both A_1 and A_2. Depending on the equipment, the signals from both sensors should be captured and the trigger channel should be the A_1 sensor attached closer to the impact location.

Side mount accelerometers are recommended and the sensors can be glued, bolted, or held by wax or putty to the side of the pile. Under wet condition or unclean surface, bolts are preferred to attach the accelerometer to anchors installed in the concrete piles. For timber piles, the side mount sensors can be directly attached to the side of piles using lag bolts.

If side mount sensors are not available, top mount sensors can be used (if they can be bonded parallel to the pile axis). Possible sensor mounting setups are shown in Figure 16.

Impact Technique

Figure 17 shows three possible impact spots. Directly impacting above the pile generally gives the better signal if the connection between the pile top and structure is solid as shown in Figure 17a. If the top impact is not possible or the connection between the pile and existing structure is not solid, the side impact may be tried, with the attempt for the impact to still be as parallel to the pile axis as possible. There are two methods of side impact as follows:

1. If allowed, a notch is created to apply impact as shown in Figure 17b;
2. Otherwise, a block for impact is attached to allow impact axially. The material and attachment method of the impact block will affect the signal quality (Figure 17c).

When using a side impact, a notch is preferred since the impact can be applied without additional inference from an impact block attachment. Due to the potential complexity of existing structures, it is recommended that testers try to apply impacts both at the top and side. For smaller size piles, impacts may be applied at a location 90 degrees away from the gage. It is suggested to apply impacts at least one diameter above the top accelerometer location.

The selection of right hammers is another important factor to obtain reasonable data. The frequency content in the input pulse induced by the hammer impact are affected by the contact between impact surface and hammer tip, the hammer tip material and the hammer weight. If the impact spot is not smooth, higher frequency noise will be induced. A harder hammer tip and/or lighter weight will generate higher frequency content. The higher frequency input helps identify the small defects and defects near the impact spot, but their energy decays faster and may reduce the chance to detect the toe or defects in the lower portion of the pile. A softer hammer tip (such as using Lexan instead of steel) or a heavier weight will generate a lower frequency input pulse. For piles under existing structures, due to multiple reflections from the interface between the pile and structure and/or impact input energy splitting to different wave travelling paths, more input energy with a lower frequency content is preferred when comparing to traditional testing at the pile top. Since there are several factors affecting the input frequency content and no hammer design is standard, it is recommended that different sizes of hammers should be tried to find the best hammer for any particular situation.

Location and Distance between Two Sensors

To Determine Wave Speed

The accuracy of wave speed determination depends on the accuracy of the measurements of the distance between the two sensors and the time (T) for the wave to travel from A_1 to A_2. Increasing the distance between the two accelerometers and/or increasing the sampling frequency generally improves the accuracy of the wave speed determination. If the sample frequency is 150,000 hz and the sensors are 1.5 m (5 ft) apart, the accuracy could be within 2%. Thus the distance should be the largest that it can practically be. Please note that the wave speed determined only represents the averaged value between two sensors, which may not represent the overall wave speed for whole pile.

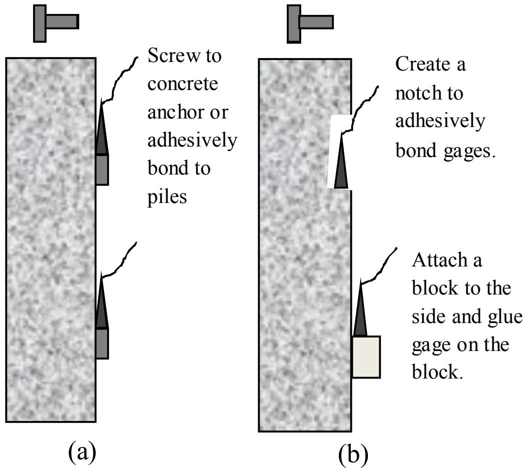
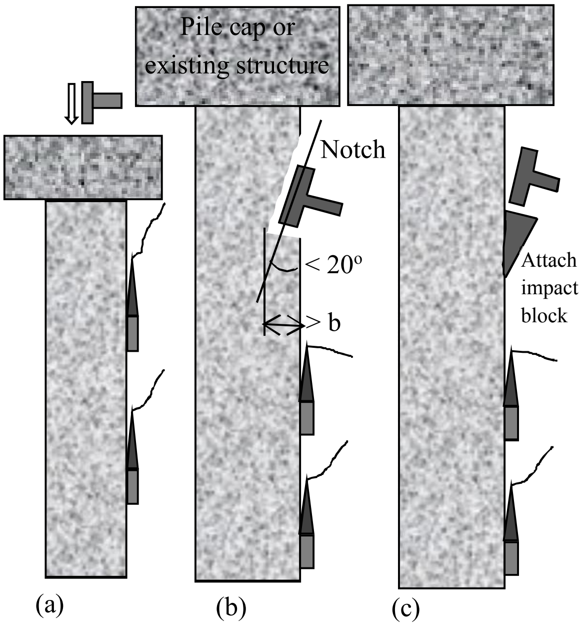


Figure 16. Sensor Mounting: a) using side mount sensors; b) using top mount sensors



b – Hammer tip size

Figure 17. Impact Locations and Methods: a) Impact on top the structure above pile; b) Impact on notch created on the side of pile; c) Impact on a block attached to the side of pile

To Separate Downward and Upward Traveling Velocities

Since the mathematical manipulation is performed (Equations 1 and 2) between two velocity records acquired from two accelerometers at different locations, it is very important to meet the following requirements:

1. Same type of sensors;
2. Correct calibration factors;
3. The cross section of pile between A_1 and A_2 should be uniform.

The distance between the sensor connected to the triggering channel and the impact location or the nearest cross section change location should be at least larger or equal to 0.3 m (1 ft); one diameter of pile is preferred. The distance between two sensors is suggested as between 0.75 and 1.5 m (2.5 and 5 ft). It could be larger for a wide input pulse with lower frequency content.

CONCLUSION

As a NDT method, LST has been widely used as a quality assurance tool for deep foundations. However, to test piles under an existing structure, the traditional LST with only one accelerometer, or one acceleration plus impact force, is often difficult to interpret due to the multiple downward travelling waves induced by the initial hammer impact and reflections from the existing structure. The extended LST method with two acceleration measurement helps to separate upward traveling waves from downward traveling waves, and therefore to determine the reflections from potential defects and the pile toe. The case study presented in the paper is a good example of its successful application. To help assist in future applications, recommendations have been presented.

REFERENCE

Johnson, M., and Rausche, F. (1996). Low Strain Testing of Piles Utilizing Two Acceleration Signals, Stress Wave 1996, Orlando, FL, p.859-869

Liang, L., and Rausche, F. (2011). Quality Assessment Procedure and Classifications of Cast-In-Place Shaft using Low Strain Dynamic Test, Proceedings from Deep Foundations Institute 36th Annual Conference on Deep Foundations.

Likins, G., and Rausche, F. (2000). 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, pp 211-218.

Mullins, G. (2008). Thermal Integrity of Drilled Shafts, Presentation to the Florida Suncoast Chapter, ACI.

Rausche, F., Likins, G., Liang, L. (2008). Challenges and Recommendation for Quality Assurance of Deep Foundations, Proceedings of the 33rd Annual and 11th International Conference on Deep Foundations. Deep Foundations Institute: New York, NY (CD-ROM)

Webster, K., Rausche, F. and Webster, S. (2011). Pile and shaft integrity test results, classification, acceptance and/or rejection, TRB 90th Annual Meeting, Washington, D.C.