

Comparing cross-hole sonic logging and low-strain integrity testing results

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ABSTRACT: Integrity issues for cast-in-place piles have resulted in a serious need for NDT inspection methods to detect the extent and location of serious flaws and prevent failures under service conditions. Integrity inspections performed after installation are often the most reasonable alternative available to assess the shaft quality. The two most common methods are impact echo from a small hand held hammer at the pile top, and cross hole ultrasonic transmissions along the shaft between parallel tubes. While different in technique they each have advantages and weaknesses. This paper discusses the similarities and differences, and advantages and disadvantages.

Cross-hole sonic logging and low-strain impact echo integrity testing were both specified as quality control measures for a project which utilized 1.37 m (54") diameter drilled shafts as abutment foundations. Both cross-hole sonic logging and impact echo integrity testing indicated defects in several shafts. Subsequent coring confirmed these defects. The results of the two test methods are presented and compared with each other, and with the coring.

1 INTRODUCTION

Cast-in-place (CIP) concrete piles are often chosen as a deep foundation alternative where challenging soil conditions exist and/or where vibrations from pile driving are unacceptable. Although quality control measures are almost always taken during the initial installation of the foundations, it is often difficult or impossible to confirm the integrity of a drilled shaft during construction, particularly in wet conditions. Camp et al. (2007) found that, out of 441 drilled shafts tested on multiple projects in South Carolina, approximately 75% of the projects had at least one shaft containing an anomaly and 33% of all shafts tested contained at least one anomaly. Drilled shafts often have significantly higher design loads than driven piles and therefore are less repetitive (Likins et al. 2007). Because of the relatively high probability of drilled shafts having anomalies and low repetitiveness, quality assurance of each drilled shaft is essential for each project.

Non-destructive test (NDT) methods after installation have become the standard in quality assurance of drilled shaft foundations. Several methods are available to perform this testing. Among the most common methods of NDT testing are cross-hole sonic logging and low-strain integrity testing. Individually, each test method has its own advantages and weaknesses inherent in the test

method. These advantages and weaknesses are discussed in this paper. When both test methods are used in conjunction, certain characteristics of a potential defect may be clarified.

This paper presents a case history where anomalies are indicated by both test methods. The results of the two test methods are compared. Core drilling also confirmed the anomalies as defects.

2 CROSS-HOLE SONIC LOGGING

Cross-hole sonic logging (CSL) is a NDT method which involves ultrasonic signal transmission through the shaft between two parallel water filled access tubes. The access tubes are often tied to the rebar cage and cast permanently into the shaft. The total number of access tubes typically depends on the diameter of the shaft. A transmitter probe and a receiver probe are lowered to the bottom of the shaft in separate access tubes. Measurements of the signal transmission are collected approximately every 5 cm as the probes are raised to the top of the shaft. The cables attached to the probes are pulled through calibrated encoder wheels which can accurately determine the depth of the probe during testing. A collection of measurements from one access tube to another are called a profile. Profiles are collected from all combinations of access tubes. The test method is



Figure 1. Cross-Hole Sonic Logging.

described in ASTM D6760 (2002). Fig. 1 shows a typical method for collected CSL data.

2.1 CSL Result interpretation

The interpretation of CSL results requires experience and understanding of the capabilities and limitations of the method. Shaft quality assessment from CSL is primarily based on the first arrival time (FAT) of the signal. The concrete wave speed can be estimated by dividing the distance between the access tubes by the FAT. The wave speed of concrete can be used as a judgment of the overall concrete quality because wave speed is related to concrete compressive strength. However, during placement of the rebar cage or concrete, the access tubes often move slightly out of parallel and ultimately the distance between the tubes is not always constant with depth. Therefore, it is more practical to evaluate the FAT as a relative measurement for each individual shaft, comparing signal delays to a “running” average of data from the same shaft. Often a running average of approximately 75 consecutive data points, which would represent approximately the surrounding 3.75 m, are averaged for comparison to evaluate a local defect.

Signal strength is another important measurement for evaluation of CSL data. The signal strength is converted to signal “energy” by integrating the signal over a defined time. Relatively low energy can indicate poor quality concrete or a defect in the shaft. Often a major defect will cause both a significant FAT delay and decrease in relative energy. Interpretation of a

Table 1. Suggested CSL Results Scale

Concrete Quality	FAT Increase (%)	Energy Reduction (dB)	
Good	0 to 10	and	< 6
Questionable	10 to 20	and	< 9
Poor/Flaw	20 to 30	or	9 to 12
Poor/Defect	> 30	or	> 12

major defect from CSL is often intuitive, however, evaluating a relatively minor FAT delay or energy decrease requires engineering judgment. Likins et al. (2007) suggested the scales shown in Table 1 and actions described after.

Flaws should be addressed if they are indicated in more than 50% of the profiles. Defects must be addressed if they are indicated in more than one profile. Addressing a flaw or defect should include, at a minimum, an evaluation by tomography if the area of concern is localized, and/or additional measures such as excavation, core drilling, or pressure grouting. Defects or flaws indicated over the whole cross-section usually require repair or replacement.

2.2 CSL Advantages

- Relatively simple interpretation when a major defect is present
- No pile length limitation
- Can determine the depth of an anomaly with reasonable accuracy
- Can estimate horizontal extent of a defect if enough access tubes are present

2.3 CSL Disadvantages

- Access tubes must be cast during shaft construction (Test shaft must be preselected)
- Several factors can influence results (uncured concrete, debonding, etc.) however, the cause for the FAT delay and/or energy decrease often cannot be determined
- Only concrete between access tubes can be assessed
- Evaluation often requires experience and engineering judgment when results are complicated or not outwardly conclusive

3 LOW STRAIN INTEGRITY TESTING

Low-strain integrity testing, also known as Pulse Echo Method (PEM) or Pile Integrity Testing (PIT), is a NDT based on wave propagation theory. The pile top is impacted with a hand held hammer and the resulting pile top motion is measured via an accelerometer attached to the pile top. The hammer impact creates a low strain compression stress wave that propagates down the pile. The wave is reflected when a change in “impedance”, the pile toe, or soil resistance effects

are encountered. Impedance is related to a pile's cross sectional area, elastic modulus, and stress wave propagation speed. An impedance reduction causes a reflected tensile wave (a increase in the velocity curve) and an increase in impedance causes a reflected compressive wave (a decrease in the velocity curve). High soil resistance can also cause compressive reflections which can sometimes be minimized through filtering techniques. The test method is described in ASTM D5882 (2007). Fig. 2 shows a typical field test using the pile integrity tester.

Low strain integrity testing has many potential applications. The most typical application is to evaluate newly constructed shafts as a quality control measure. Recently, the evaluation of existing foundations has become more relevant in urban construction or historical structures. Low-strain integrity testing can be an effective tool in evaluating shaft lengths and quality. Several papers have been published regarding estimating pile lengths using low strain integrity testing including Morgano (1996) and Massoudi and Teferra (2004).

3.1 Low Strain Integrity Testing Result Interpretation

In order to fully evaluate shaft integrity using low strain integrity testing results, a clear toe reflection in the velocity record must be observed. When the length of the shaft is known, the appropriate material wave speed can be applied to the record. Tensile reflections that occur prior to the toe reflection can be investigated to determine if any impedance reductions occur in the shaft.

Several factors can deplete the strain wave and therefore diminish any observable toe reflection. These factors include high soil resistance, several minor or one major impedance change, and excessive length. Piles with length to diameter ratios above 30 often have excessive damping due to soil resistance and/or pile material properties which deplete the strain wave and cause no observable toe reflection, although this rule can sometimes be



Figure 2. Low Strain Integrity Testing.

deviated and piles with a greater ratio can be reasonably tested under special circumstances (Massoudi and Teferra, 2004).

3.2 Low Strain Integrity Testing Advantages

- Minimal pile preparation required
- Relatively quick and inexpensive; allowing the possibility for every pile to be evaluated
- Can provide depth and severity information regarding major defects
- Can potentially evaluate length and quality of existing foundations
- Test shafts can be selected after installation

3.3 Low Strain Integrity Testing Disadvantages

- Inconclusive results or complicated signals can be caused by several factors
- Records required experienced interpretation
- L/D limitations
- Horizontal extent of a defect often cannot be evaluated
- Accuracy of length or depth to defect is dependent on an assumed wave speed

4 TEST METHOD COMPARISON

Both of these NDT methods are effective tools in quality assurance and foundation evaluation. The advantages and disadvantages of each individual test method have been discussed. The two test methods also inherently have similarities and differences in their application and results.

4.1 Test Method Similarities

- Non- destructive and repeatable
- Time dependent – results depend on concrete curing (with respect to wave speed)
- Evaluate concrete quality and overall shaft acceptability, however often cannot determine the cause or material properties of a defect, only that it is present
- Require experienced interpretation of results and engineering judgment in presenting results
- Can reasonably be performed on all production shafts

4.2 Test Method Differences

- CSL can only evaluate the concrete between access tubes while PIT can evaluate the full cross section as well as profile of the shaft
- CSL can estimate depth, horizontal position, and extent of a defect, PIT only indicates the depth and only a very rough estimate of the extent
- CSL is effective in identifying a “soft toe” condition while PIT cannot be reliable for this

application (due to variations in concrete wave speed)

Both of these test methods can be used on the same shaft. In conjunction, the combined test results provide a more comprehensive evaluation of the shaft than either single test alone. For example, if PIT testing indicates an impedance decrease at a certain depth however CSL results do not indicate FAT delays or energy decreases at the corresponding depth, it is likely that the impedance decrease indicated from PIT results is from a reduction in cross section and not from a material quality issue.

5 CASE HISTORY

1.37 m (54") diameter drilled shafts were chosen as the abutment foundation for an airport bridge. Both cross-hole sonic logging and low strain integrity testing were specified. Four access tubes were cast into the shafts to facilitate CSL testing. The amount of each type of testing was to be determined from the early production shaft test results. Several of the early production shafts were found to be defective and, consequentially, both types of testing were performed on all 66 production shafts.

5.1 Shaft with major defect

Fig. 3 shows results from low strain integrity testing (top) and the major diagonals from CSL testing (bottom). The “waterfall” diagram from CSL in Fig. 3 shows quite clearly a delay in first arrival time and energy losses between 11.0m and 14.8m. The defect was indicated in all profiles. FAT delays ranged from 40 to 55% and energy decreases ranged from 11.1 to 15.2 dB. The pile top velocity curve from the integrity testing indicated gradual impedance decrease beginning at approximately 8 m and a very strong tensile reflection (major impedance decrease) at approximately 11 m (shown in shaded area). Both methods clearly indicated a defect in this shaft. The combination of the two test method results appears to indicate that the shaft reduces in diameter from 8 to 11 m and the material below 11 m is defective. Based on the results from both CSL and PIT, the shaft was cored. Fig. 5 shows a picture of the core results from the shaft in Fig. 3. Sand (shown in a jar) was encountered at approximately 11 m depth below the top of concrete, which corresponds well with both test method results. It is believed that the soil caved in the time between placement of the rebar cage and when concrete was placed.

The pile top velocity curve from PIT in Fig. 3 shows what could be evaluated as a toe reflection. However, it is not possible for the low strain wave to propagate through soil, which was proven present through coring results, therefore it is not reasonable to state that the reflection is from the pile toe, only that no

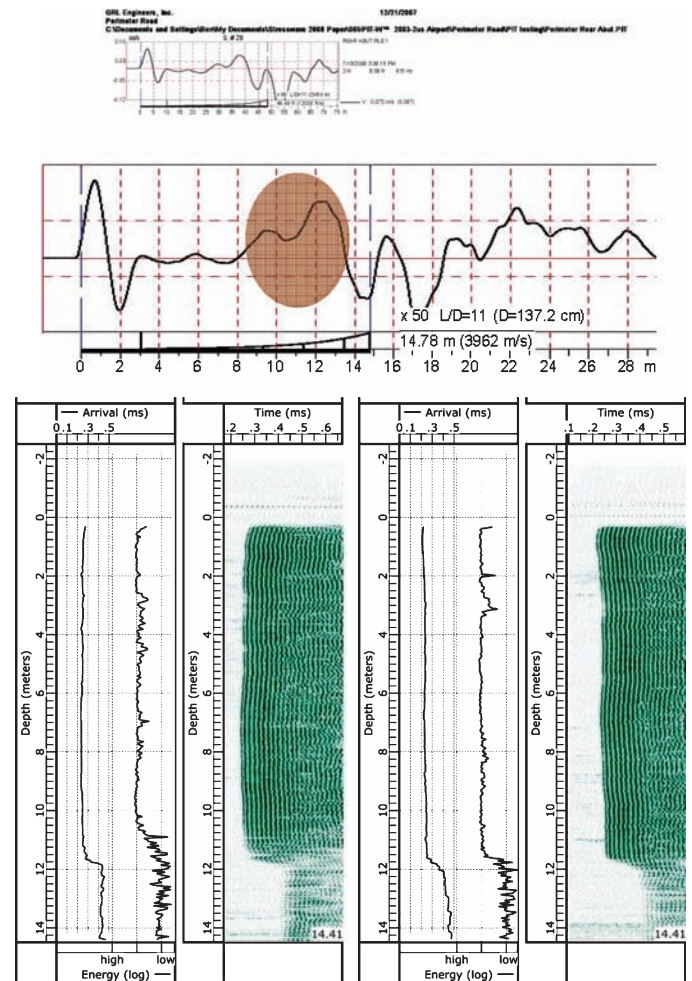


Figure 3. PIT Results (Top) and CSL Results (Bottom) from a defective shaft.

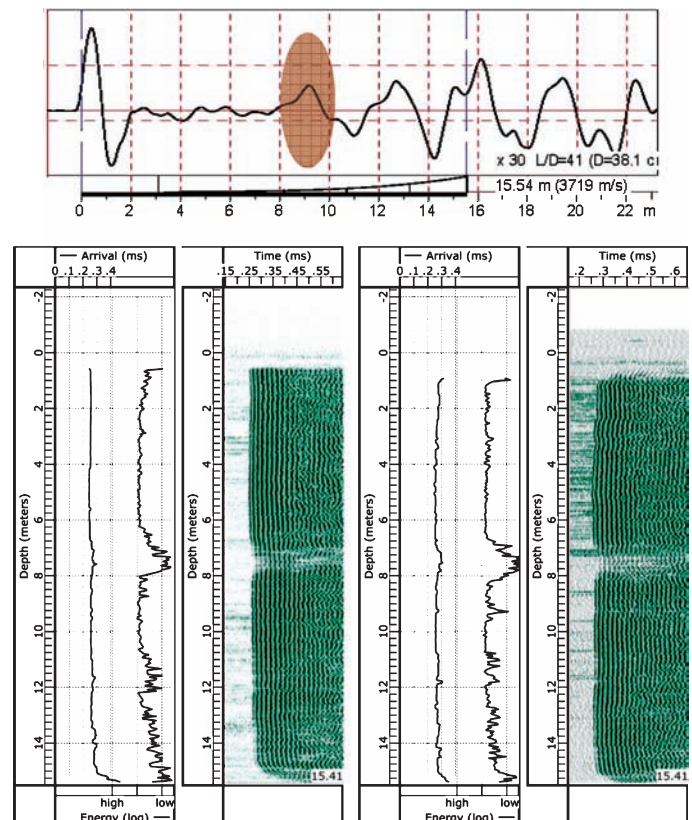


Figure 4. PIT Results (Top) and CSL Results (Bottom) from a shaft with a flaw.



Figure 5. Core from above shaft – sand (in jar) was encountered at approximately 11 m depth.

determination of shaft integrity is possible below the major impedance change. If only integrity testing had been performed, the reflection at approximately 14.8 m may have been mistaken as a reflection from the pile toe; however, the large tensile reflection at approximately 11 m clearly indicates a defect in the shaft.

5.2 Shaft with a “flaw”

Fig. 4 shows PIT and CSL results from another shaft, again with low strain integrity testing results on top and the two major diagonal profiles from CSL on the bottom. The CSL results indicated FAT delays ranging from 21 to 26% and energy decreases ranging from 10.8 to 12.9 dB. Based on the suggested criteria in Table 1, this anomaly would be classified as a flaw (except for one profile which had an energy decrease of 12.9 dB, which would classify it as a defect). The flaw was indicated in all CSL profiles at approximately 8.0 m depth. The pile top velocity curve from PIT indicates an impedance decrease at a similar depth (shown in shaded area); however, the tensile reflection is relatively minor compared to the reflection in Fig. 3. A reflection occurs at the depth corresponding to the toe and could be accepted as the pile toe, however, there appears to be several impedance changes prior to the toe and therefore, this reflection may or may not be accepted as a reflection from the pile toe. The concrete was drilled without at core barrel; therefore, no sample

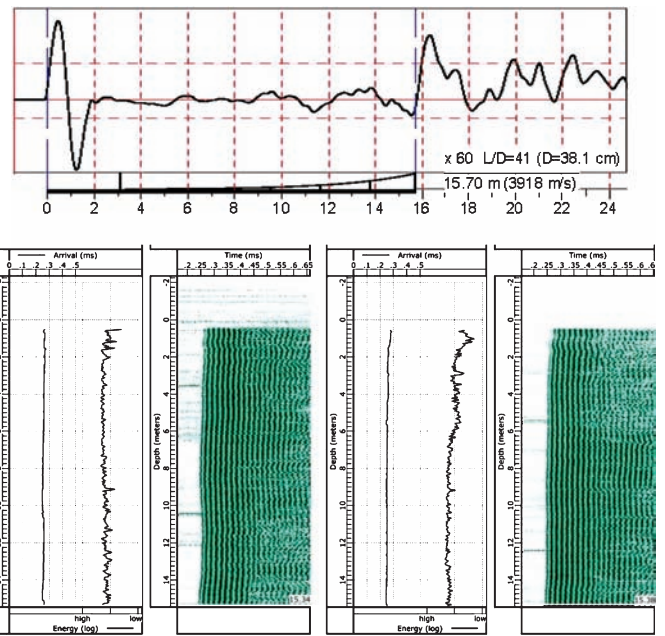


Figure 6. PIT Results (Top) and CSL Results (Bottom) from a shaft free of flaws or defects.

was collected. At approximately 7.8 m depth, a relatively soft zone was encountered (apparent from the rate of drill penetration). The soft zone was approximately 0.1 to 0.2 meters thick.

5.3 Shaft free of flaws or defects

Fig. 6 shows typical PIT and CSL records from a shaft with no detectable flaws or defects. The CSL results indicate a consistent first arrival time and energy measurement. The PIT record is relatively flat throughout the length of the shaft (no major impedance changes) with a clear reflection from the toe of the shaft.

5.4 Case History Results

66 shafts were tested with both cross-hole sonic logging and low-strain integrity testing. 20 shafts had what is often called a “soft toe” condition, where a small amount, typically less than 1 foot vertically, of soil is present at the bottom of the shaft. CSL testing can clearly show a soft toe condition as long as the access tubes are close enough to the bottom of the shaft. The soft toe effectively reduces the shaft length by a small amount. Because of the variability of the wave speed in concrete, the small change in pile length cannot be detected with the low-strain test method. For this particular project, because these piles were designed as friction piles and did not rely on end bearing, piles with a soft toe condition were deemed acceptable.

CSL indicated nine shafts which, based on the suggestions in Table 1, should have been addressed. PIT testing indicated potential defects in six of these nine shafts (four of which also indicated a clear toe reflection). For the three remaining shafts, PIT showed no indication of a defect in the shaft (two of these

shafts indicated a clear toe reflection). Four piles were cored (or drilled). In three of these cases, the defect was encountered. On this project, 4 additional shafts were drilled to replace shafts which were deemed defective based on CSL, PIT, and coring results.

6 CONCLUSIONS

Low-strain integrity testing and cross-hole sonic logging are both effective tools in the quality control and quality assurance of deep foundations. The results from either test, however, require experienced interpretation as well as an understanding of the test methods and their limitations.

Low strain integrity testing is relatively inexpensive and with only minimal pile preparation, can reasonably be performed on all production piles. However, limitations inherent in the test method can sometimes cause complicated or inconclusive results. Also, the CSL, PIT, and coring results presented in Fig. 3 support the idea that accurate determination of shaft integrity below a major impedance change from PIT data is not possible.

While more preparation is required (casting access tubes into the shaft) for CSL testing, it is also reasonable to perform testing on all production shafts. CSL provides more ability to quantify a defect in the shaft and allows for accurate determination of shaft quality below a major defect, but is limited to evaluation of the concrete within the access tubes.

The case history presented in this paper demonstrated cases in which both types of testing indicated, or did not indicate, anomalies in the shafts. While this is often the case, there were some shafts in which cross hole testing indicated an anomaly and PIT did not. When either of these testing methods are utilized, individually or in combination, the limitations should be understood when interpreting the results.

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