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Defect Detection and Examination of Large Drilled Shafts Using a New Cross-Hole Sonic Logging System

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ABSTRACT

Drilled shafts and other mixed or cast-in-place concrete deep foundation elements can be costly solutions. These foundations usually carry very high design loads, and often serve as a non-redundant, single load-carrying unit. These conditions have created a need for a high-level of quality assurance and control applied to each in-place constructed deep foundation element.

The non-destructive testing method, Cross-Hole Sonic Logging (CSL), currently offers the most reliable technique for assessing the integrity of in-place constructed deep foundation elements. Recent years have seen progress in CSL instrumentation, taking advantage of the available computer technology. The software applications, however, have greatly fallen behind, thereby limiting the effectiveness and potential of the CSL method and deep foundations integrity testing in general.

A new, original CSL testing system by the name of PISA (Pile Integrity Sonic Analyzer) makes use of an innovative software and data acquisition system, hence representing the state-of-the-art in deep foundation integrity testing. The PISA has the capability to show real-time graphical information during logging, including planar tomography, which can identify the boundaries of a compromised zone within the foundation element. The equipment operates completely in a Windows^{TM} graphical environment allowing alphanumeric and graphical reports to be generated directly into word processing software. The real-time graphical representation during logging and the ease of reporting enables immediate, extensive on-site evaluation and decision making.

The PISA system was evaluated on several different construction sites. The obtained results from one particular site are presented, demonstrating the ease of use, accuracy of measurements and enhanced capabilities. The systems' abilities are shown to be superior to any other currently available commercial system.

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INTRODUCTION

Deep foundations integrity testing mostly applies to foundations constructed from concrete or grout, such as drilled shafts, drilled mini piles, pressure-injected footings, and precast concrete piles. Drilled shaft foundations usually carry very high design loads, and often serve as non-redundant, single load-carrying units. The integrity testing is required for quality control during construction to detect flaws in the pile (e.g. necking, cracking, void, poor quality material, etc.). Such defects are not uncommon in these cast-in-place concrete piles. As a result of the ever-increasing and demanding design requirements on these foundations, a need for a high-level of quality assurance and control has been created.

Cross-Hole Sonic Logging (CSL), is one of the more common testing methods for determining the integrity of in-place constructed deep foundation elements, such as drilled shafts and caissons. A minor variation of this method, called Single-Hole Sonic Logging (SSL) can also be used on smaller diameter drilled mini-piles and augercast piles. These methods are both non-destructive testing (NDT) methods and involve generating a sonic pulse with one transducer (transmitter) and picking the signal up with another transducer (receiver). The transducers typically consist of a geophone or accelerometer. The methods differ only in the number of tests per pile and the location/orientation of the transducers within the pile.

Significant improvements and advances in instrumentation, data acquisition hardware, and computer technology have been made in recent years. The software applications, however, have greatly fallen behind and have not taken full advantage of the existing technological infrastructure, thereby limiting the effectiveness and potential of the CSL method, as well as other deep foundations integrity testing methods (Chernauskas and Paikowsky, 1999).

A new state-of-the-art CSL testing system, however, has recently been developed that utilizes unique software to take advantage of the new hardware (Amir and Amir, 1998a). This system is called the PISA (Pile Integrity Sonic Analyzer). The PISA is based on a lightweight, portable, pen touch, computer that operates in a Windows graphical environment. This system is easy to use and efficient with regard to its ability to make the collected data available in a real-time manner. The following paper provides the basic background theory on the CSL integrity testing method, a description of the PISA system, and a summary of a recent case history including large size rock socketed drilled shafts, defects detection, and verification.

OVERVIEW OF ULTRASONIC INTEGRITY TESTING METHODS

Cross-Hole Sonic Logging

Cross-Hole Sonic Logging (CSL) is the most common integrity testing method for drilled or cast-in-place foundations. A piezoelectric transducer is used to generate a signal that propagates as a sound (compression) wave within the concrete, while another transducer is used to detect the signal. Each transducer is placed into a vertical PVC or steel tube that has been attached to the reinforcement cage and filled with water prior to the concrete placement. The water acts as a coupling medium between the transducer and the tube. A typical tube arrangement and testing principles are presented in Figure 1.

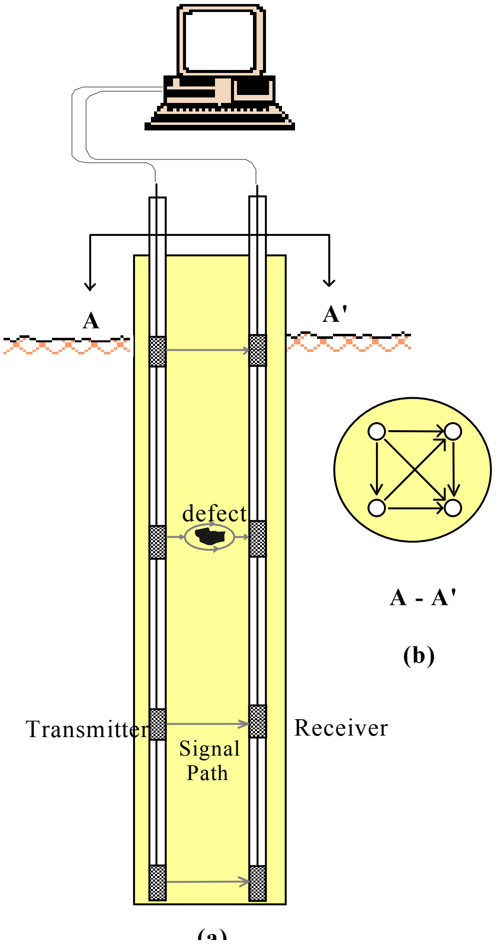


Figure 1 Typical CSL Testing Set-up Showing (a) Transmitter and Receiver at Different Depths, and (b) Plan View of the CSL Tubes with Possible Test Combinations.

The source and receiver transducers are lowered to the bottom of their respective tubes and placed such that they are in the same horizontal plane. The emitter transducer generates a sonic pulse (on the order of 10 pulses per second), which is detected by the receiver in the adjacent tube. The two transducers are simultaneously raised at a rate of around 300 mm/s (1ft/sec) until they reach the top of the drilled shaft. Typically this process is repeated for each possible tube pair combination (perimeter and diagonals). Figure 1b shows the six tube combinations that can be tested (logged) using a configuration of 4 tubes within a drilled shaft. Increased shaft diameter calls for a larger number of tubes, which increases the number of combinations and thereby the resolution of the testing zone.

In homogeneous, good quality concrete, the stress/sound wave speed, C, is typically around 3,800 m/s (12,000 to 13,000 ft/s) and is related to the modulus, E, and bulk density (unit weight, γ, and gravitational acceleration, g) as follows:

$$C = \sqrt{\frac{E \bullet g}{\gamma}} \qquad (1)$$

If for any reason the condition of the concrete is compromised, the wave speed will be reduced relative to that of the "good or sound" concrete value. Figure 2 presents a typical sonic signal for which the propagation time between the transducers is measured. The vertical axis is the signal amplitude (microvolts) and the horizontal axis is the time (microseconds). The point where the amplitude begins to rapidly fluctuate indicates the arrival time of the signal to the receiver (a.k.a. threshold time). Since the distance between the two tubes is known, the wave speed of the concrete between the tubes can be evaluated by the following relationship:

$$C = \frac{t}{L} \tag{2}$$

This is, of course, only a rough estimate, as the picking of the arrival time, t, is not objective and the distance between the tubes, L, is only known at the top of the shaft. The signal arrival times can then be plotted with depth to generate a log for the particular tube combination as presented in Figure 3. In addition to the threshold times, the energy of each signal may also be plotted with depth. This information can be used to compare signals of one zone to another where lower energy and/or later arrival times correspond to a compromised concrete quality and/or defect.

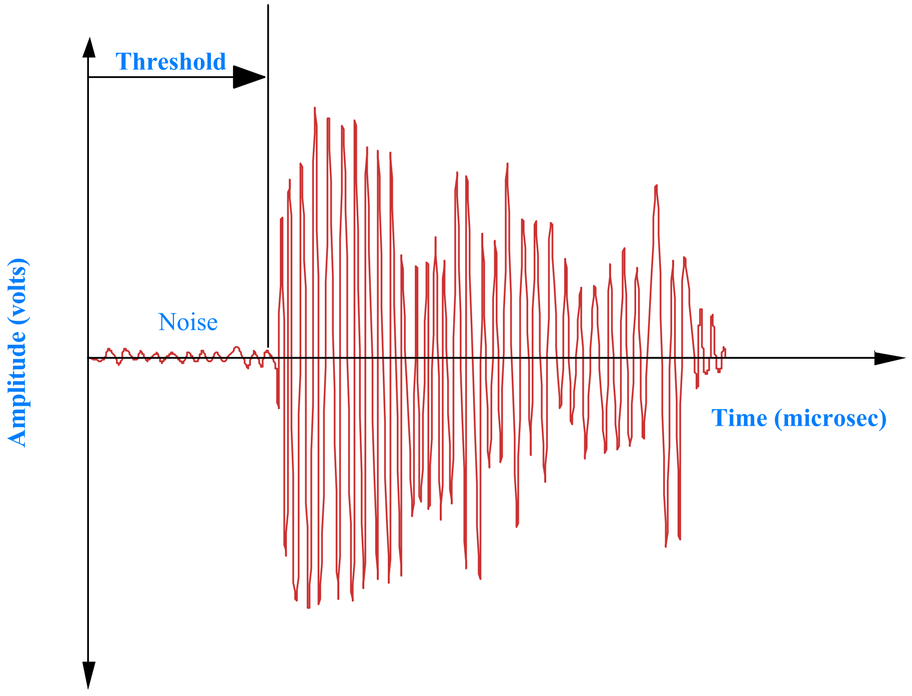


Figure 2 CSL Typical Testing Signal

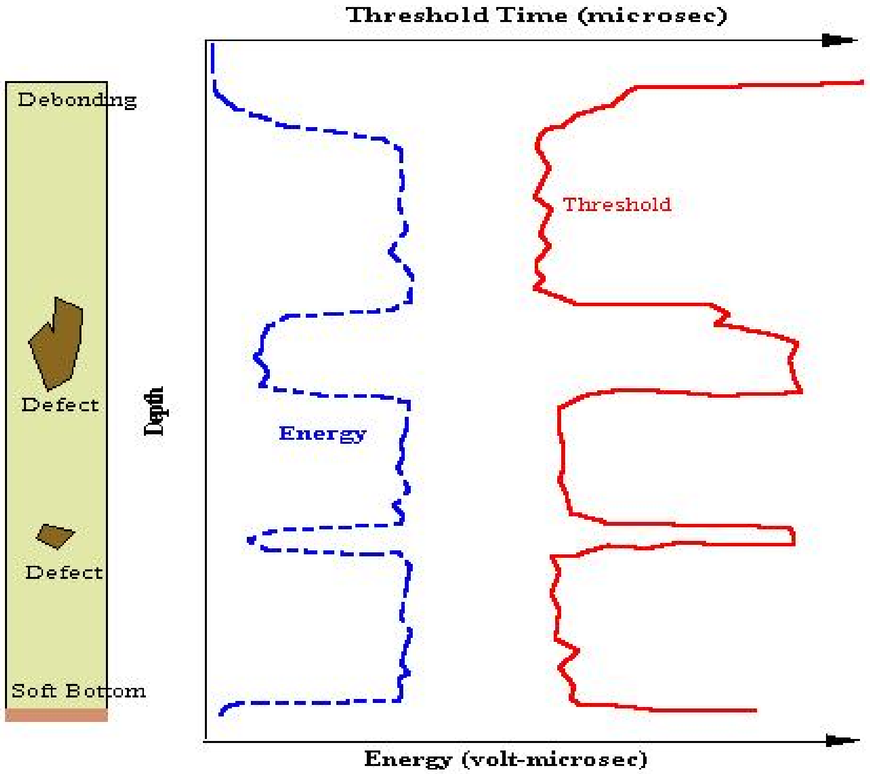


Figure 3 Presentation of CSL Test Results in the Form of Threshold Time and Energy Verse Depth

Advantages to this method include the direct assessment of pile integrity and the ability to position the transducers in different elevations to create more signals, allowing the development of a tomographic presentation of the investigated zone. The limitations of the method include detection of defects only when they exist between the tubes. The testing can be performed only on drilled shafts for which access tubes were installed. Debonding between the tubes and concrete is common if testing occurs long after the concrete placement. Testing in fresh concrete is also difficult as certain zones may cure at a lower rate, creating difficulties in the interpretation of the threshold time and energy. These zones may therefore be interpreted as poor quality concrete.

Single-Hole Sonic Logging

Single-Hole sonic logging (SSL) is a variation of the direct transmission CSL method in which the source and receiver are placed in the same tube and the signal travels in a vertical direction (refer to Figure 4). For drilled shafts and caissons, the method is limited to defects adjacent to the tube and is usually used only when a drilled shaft requires integrity assessment after construction. Due to high coring costs, typically, a single hole is advanced (often down the middle) to the bottom of the shaft or slightly below the depth where a defect is anticipated. It may also be desirable to perform SSL during CSL testing to isolate the location of a defect at a certain depth (i.e. distinguishing whether the defect identified using CSL is adjacent to the tube or in between the tubes).

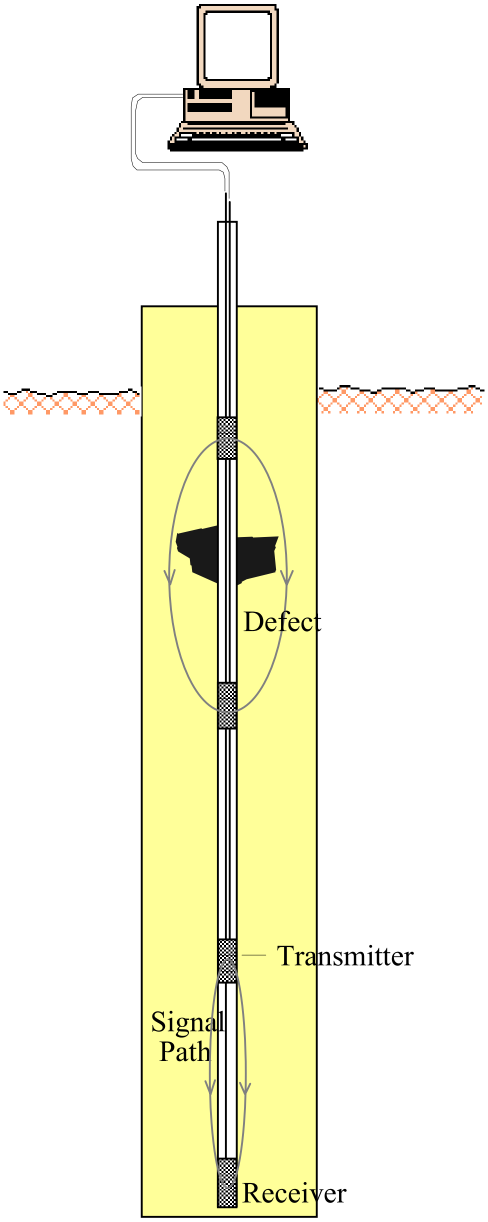


Figure 4 Typical SSL Testing Set-up Showing Transmitter and Receiver at Different Depths.

Recently, however, SSL has been performed within smaller diameter drilled mini-piles and augercast piles (Amir and Amir, 1998b). The use of SSL in these foundation types may become more commonplace in the near future, as research and experience provide insight as to the most efficient vertical placement of the tubes with respect to assessing the lateral integrity. Brettman and Frank (1996) describe a comparison between CSL and SSL tests.

THE PISA CSL/SSL TESTING SYSTEM

General

The PISA (Pile Integrity Sonic Analyzer) is a modular system allowing for adoption, upgrade and incorporation of additional integrity testing technologies. The current integrity testing options available in the PISA include cross-hole sonic logging (CSL) and single-hole sonic logging (SSL) using CHUM (Cross-hole Ultra Sonic Module) and sonic echo (a.k.a. small strain propagation) using the PET (Pile Echo Tester) module. Additional modules are currently under development.

In addition to its modularity, two advantages of the PISA integrity testing system over other systems include its software and portability. The PISA is the only Windows 95/98 based system and is also compatible with Word 2000. The software is updated periodically to incorporate new developments and algorithms that make data collection, interpretation, and report preparation easier and efficient. The PISA is lightweight (only 42.3 N (9-1/2 lb)) and self powered, hence can be easily carried around from shaft to shaft or site to site. This feature is also beneficial for air travel. The system can be also used as a standard laptop, saving the cost and space required for an additional personal computer (PC) when using a dedicated CSL testing system.

Figures 5 through 7 present photographs of the PISA system, including computer and sensors. Figure 8 presents the layout of the pile screen, where one can enter the pile information and select the tube orientation/locations. Selection of the desired tube combinations is accomplished by drawing a line between any two tubes. Figure 9 presents the data collection screen, where real-time graphical presentation of the concrete integrity is provided during testing. If a suspect zone is detected in this stage and the tomography option is enabled, the probes are lowered and raised relative to each other around the suspect zone, to further investigate and delineate the area. The signals can be examined and adjusted by manually picking the points or using preset algorithms to automatically determine the first arrival time (FAT) as shown in Figure 10. Figure 11 represents the typical graphical output for time and energy plots.

Figure 5 Photograph of the Pile Integrity Sonic Analyzer (PISA)

Figure 6 PISA System Components

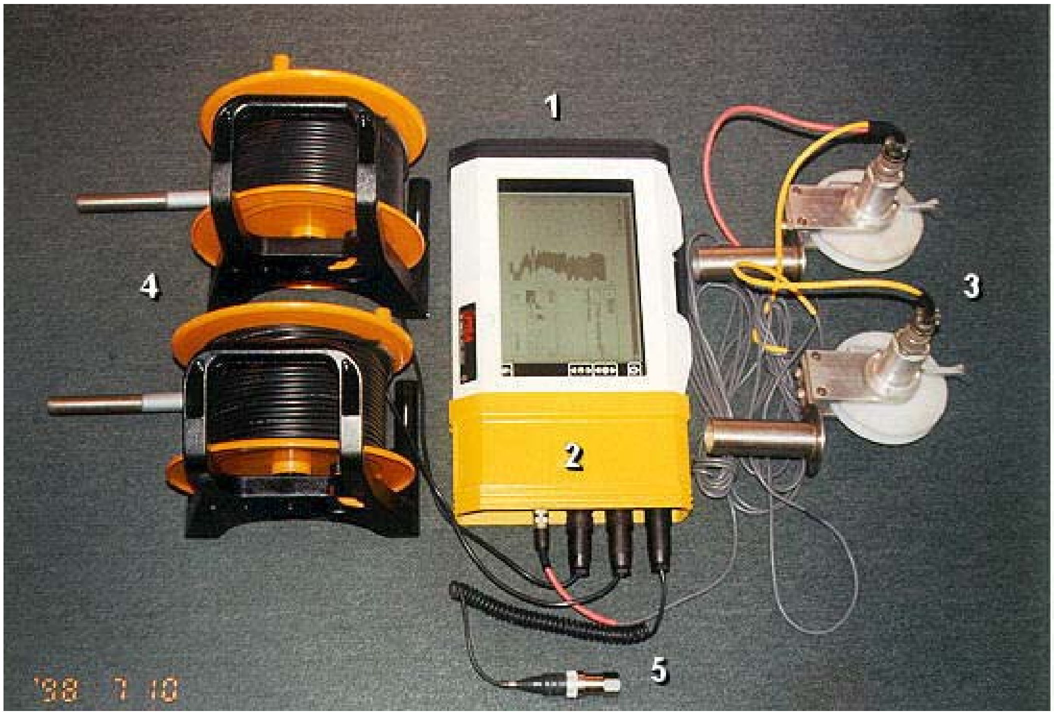
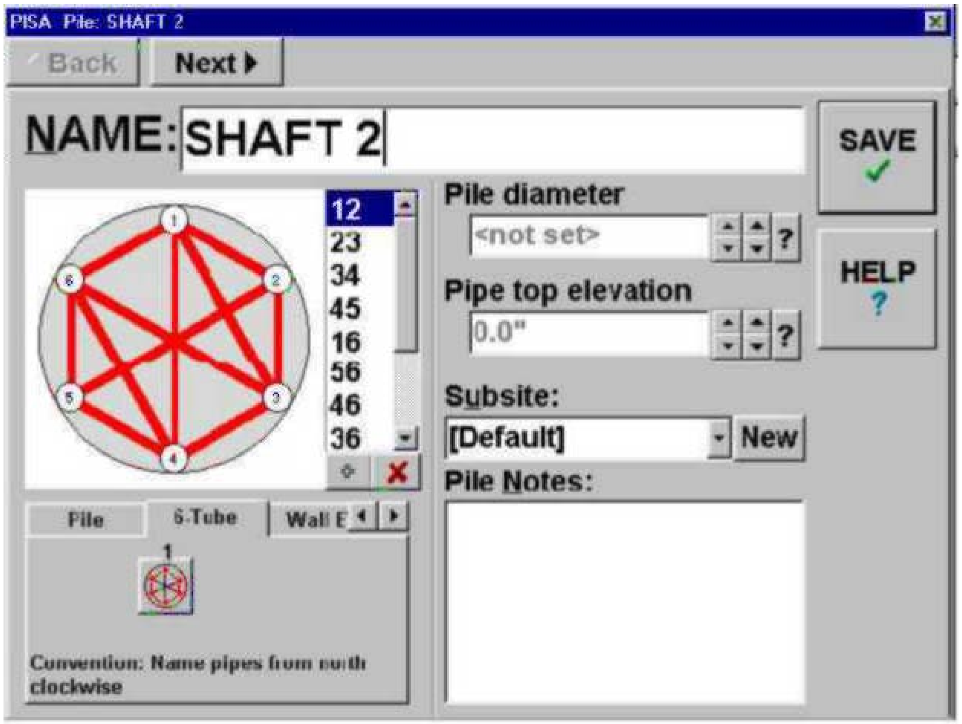


Figure 7 PISA System with CHUM and PET Modules



NAME: SHAFT 2

Pile diameter: <not set>

Pipe top elevation: 0.0"

Subsite: [Default]

Pile Notes:

Convention: Name pipes from north clockwise

Figure 8 Layout of the Pile Screen

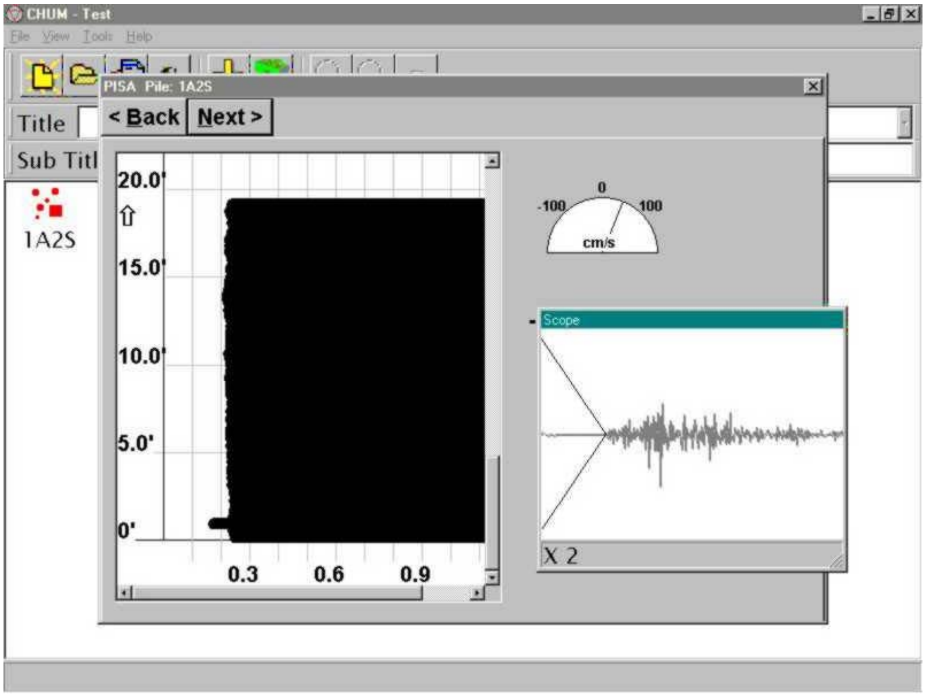


Figure 9 Data Collection Screen

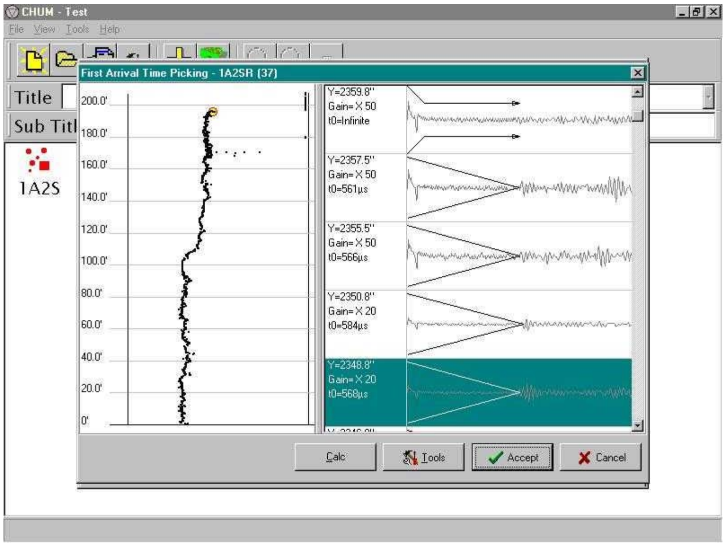


Figure 10 First Arrival Signal Identification Screen

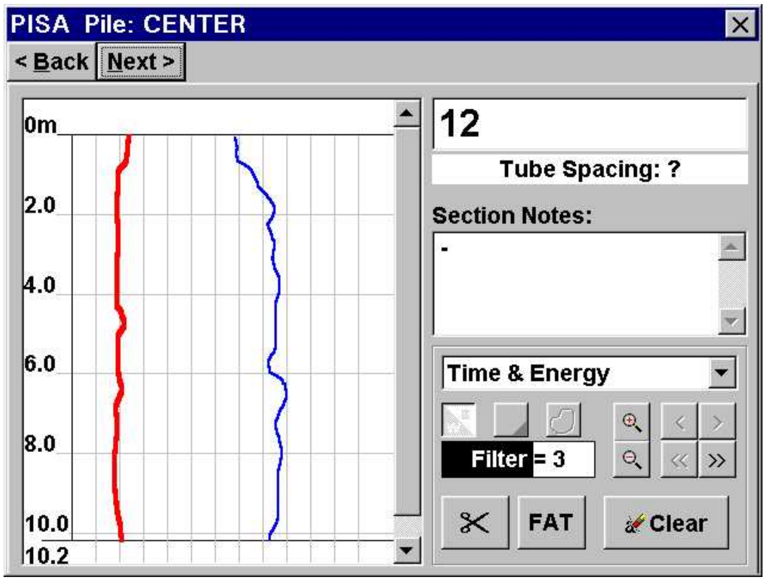


Figure 11 Typical Graphical Output for Time and Energy Plots

CASE HISTORY

CSL testing using the PISA was required for over 100 drilled shafts installed for the support of a major roadway interchange in Boston, Massachusetts. The shafts ranged between 2.1m (7 ft) and 2.7 m (9 ft) in diameter and tapered to 1.2 m (4 ft) to 1.5 m (5 ft) in diameter over the lower portion (15 m (50 ft) to 30 m (100 feet)). The total lengths varied between 36 m (120 ft) and 67 m (220 ft) below ground surface. Various penetrations into rock were required depending on the loading conditions. The shafts were constructed using temporary steel casing to the top of the clay and slurry throughout the remainder of the drilling and concrete placement process. The concrete was placed using a tremie process.

Eight schedule 80 PVC CSL access tubes were attached to the reinforcement cage and placed within the shaft prior to the placement of the concrete. The tubes were filled with water prior to placement in the shaft. CSL testing was performed primarily along the four diagonal tube combinations and four edge tube combinations as shown in Figure 12. Additional testing was performed as needed depending on the results.

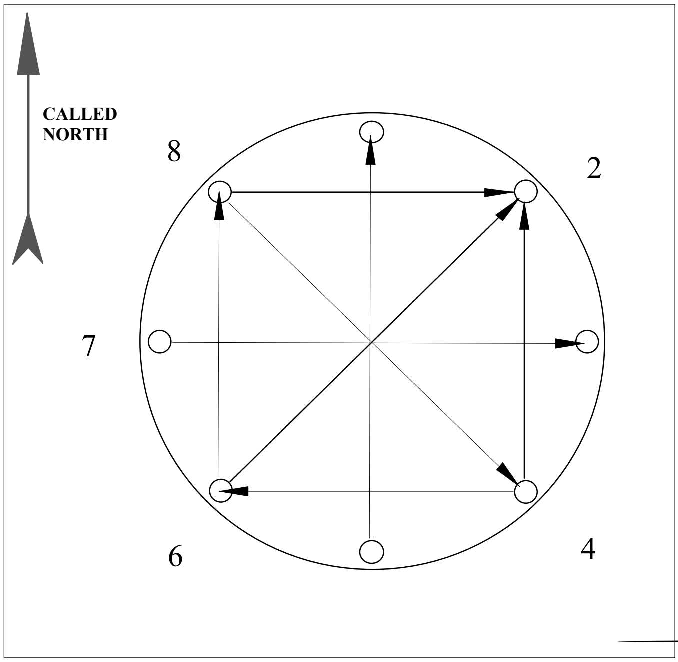


Figure 12 CSL Tube Layout

The CSL testing indicated significant anomalies in four of the first group of shafts installed for phase 1. Typical time and energy plots for the shafts (designated as "1 through 4") showing the various anomalies, are presented in Figures 13 through 16, respectively. The presented data illustrate two soft bottoms (shafts 1 and 2) and two problems in the upper 12.2 m (40 ft) (shafts 3 and 4). Table 1 summarizes the results of the repeated CSL testing performed for all four shafts. Following the testing and outline of anticipated problematic zones, a coring program was undertaken to verify the identified anomalous zones. For shafts 1 and 2, one 10.16-cm (4-in) core was drilled down the center of each shaft into the underlying bedrock. For shafts 3 and 4, multiple cores were taken between 6 m (20 ft) and 9 m (30 ft) as shown in Figures 17 and 18, respectively. The lateral extent of the suspect zones as identified by the CSL testing is presented in the two figures.

Shaft 1 - Tube combinations 4-8

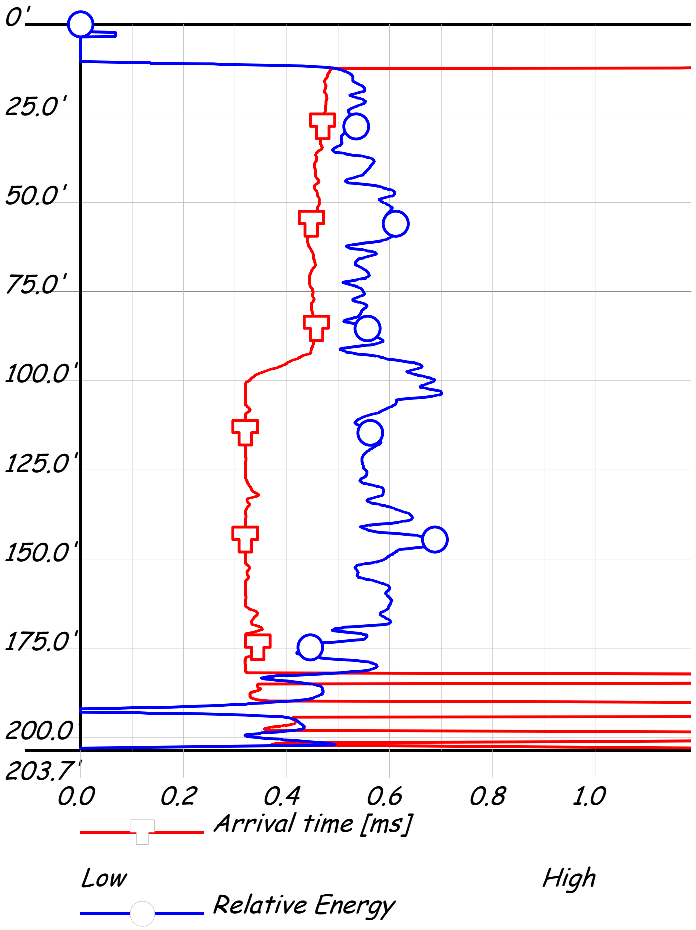


Figure 13 - Shaft 1 - Time and Energy with Depth.

Shaft 2 - Tube combinations 8-4

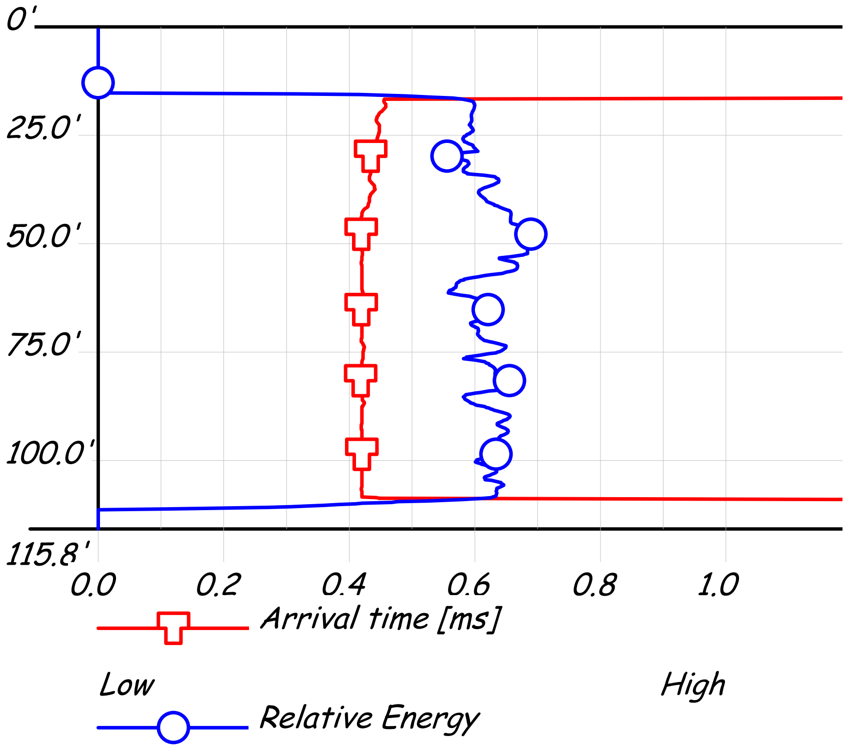


Figure 14 - Shaft 2 - Time and Energy with Depth.

Shaft 3 - Tube combination 2-6

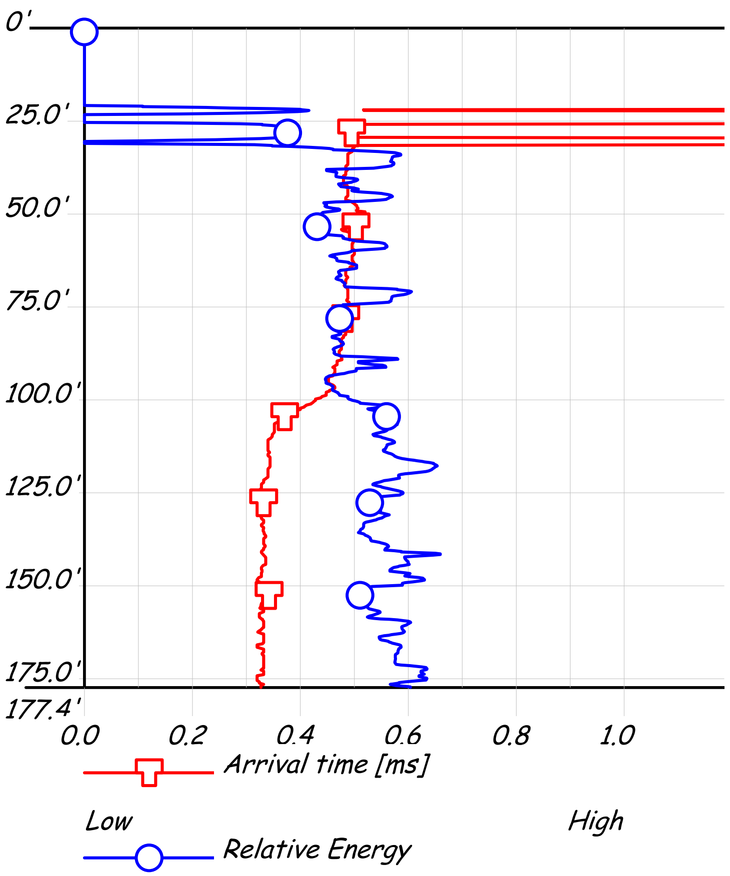


Figure 15 - Shaft 3 - Time and Energy with Depth.

Shaft 4 - Tube combination 5-7

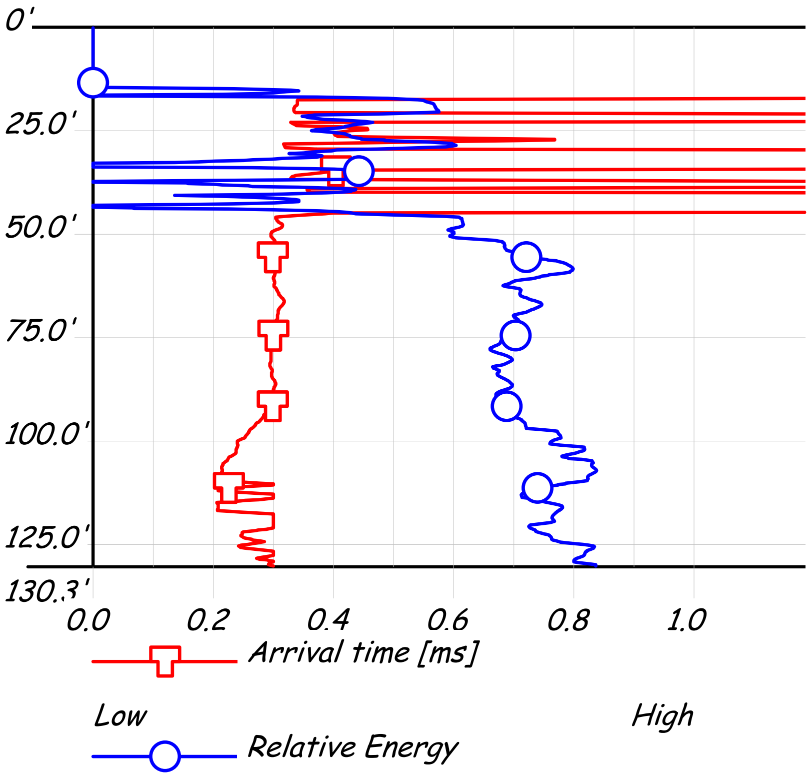


Figure 16 - Shaft 4 - Time and Energy with Depth.

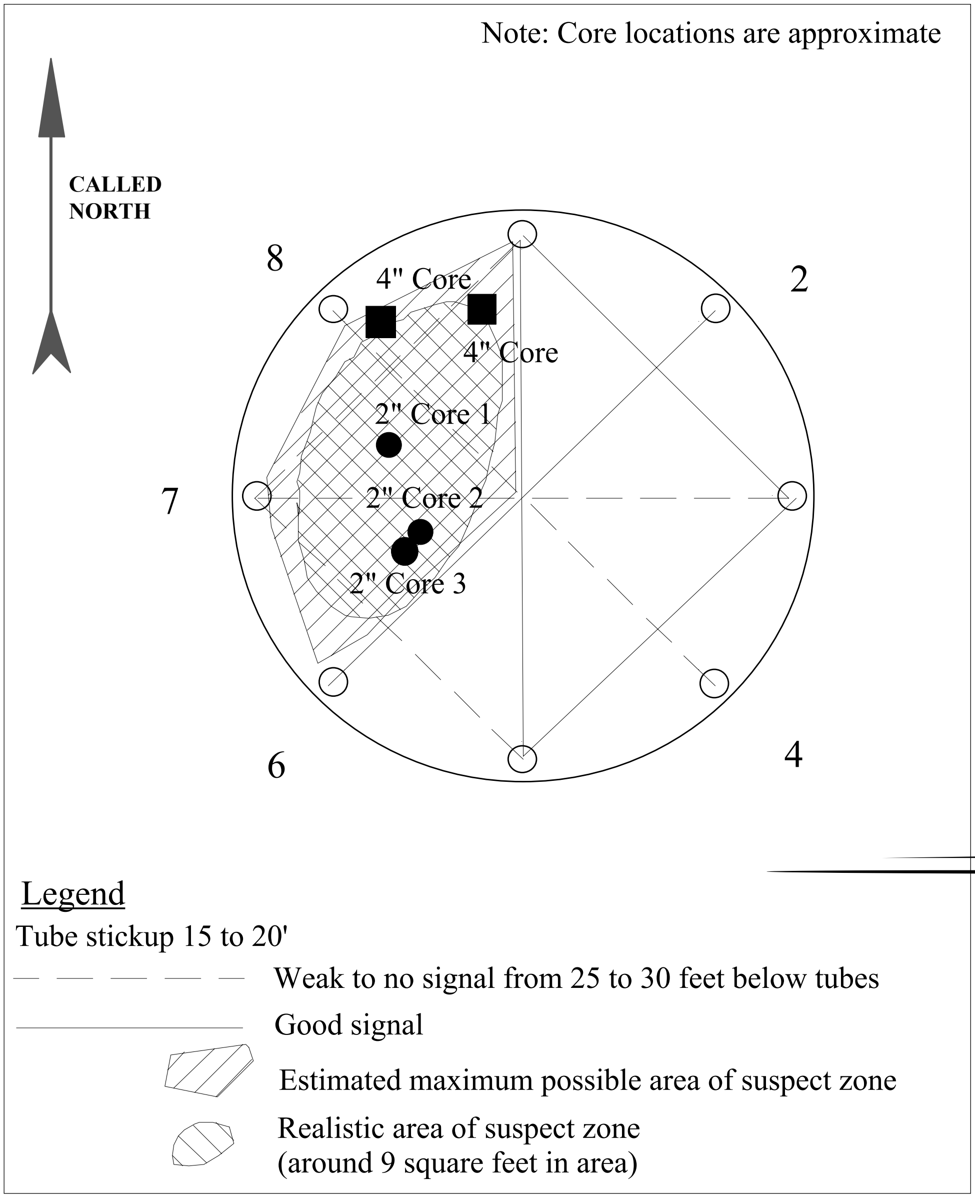


Figure 17 CSL Summary - Shaft 3

The concrete core samples retrieved from the suspect zones in shafts 1 (lower 6.1 m (20 ft)) and 2 (lower 2.4 m (8 ft)) were completely raveled, segregated, and disintegrated suggesting major discontinuity in the lower section of the shaft. The beginning of the defective concrete obtained from the coring coincided closely with the suspect zone identified during the CSL testing. These two shafts are currently undergoing repair procedures to transfer the loads through the defective zone to the underlying rock below.

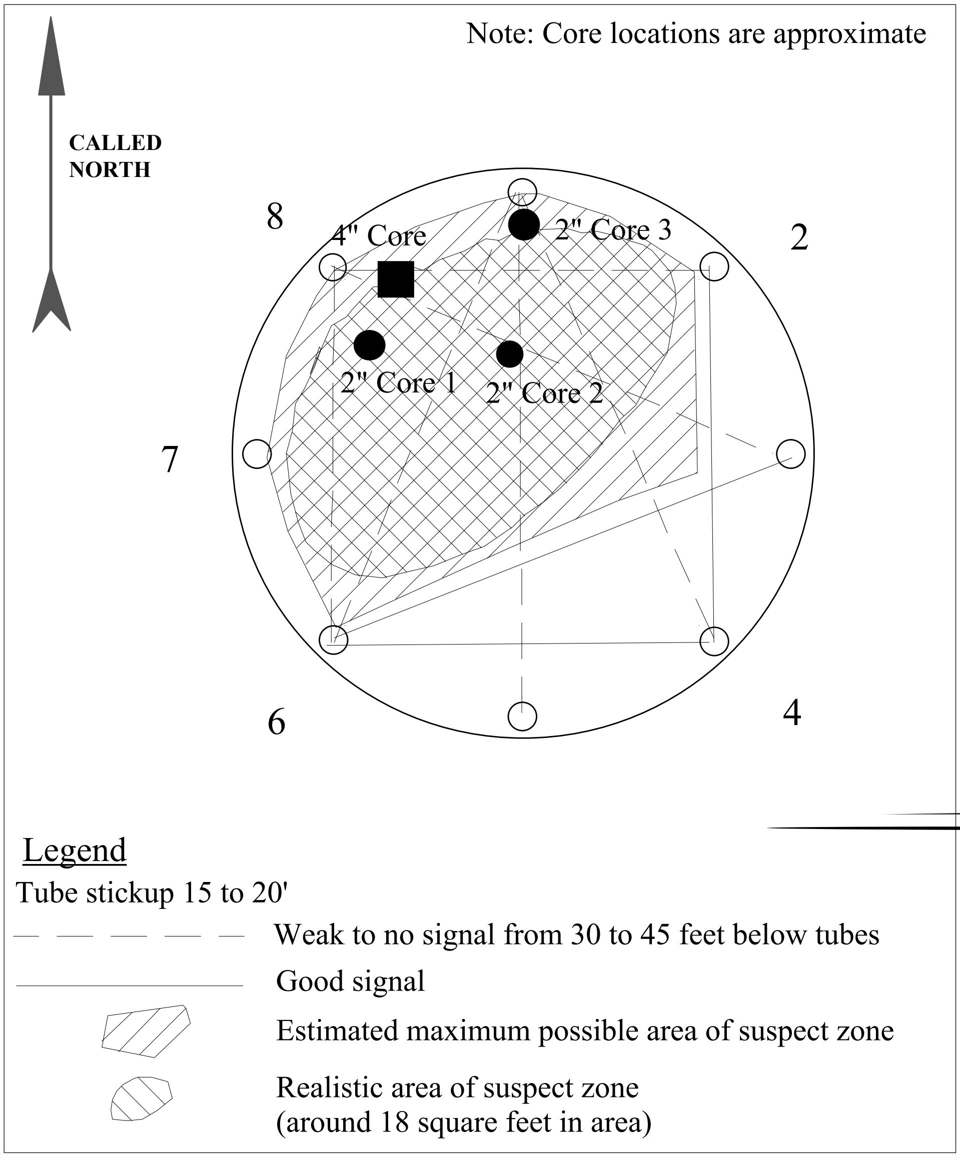


Figure 18 CSL Summary - Shaft 4

The concrete core samples retrieved from the suspect zones in shafts 3 (upper 1.5 to 3 m (5 to10 ft)) and 4 (upper 6.1 to 9.1 m (20 to 30 ft)) indicated mixed results. Moderate to severe segregation was observed in some of the cores for shaft 3. In one core, complete disintegration was observed between 1.5 to 3 m (5 to 10 ft). Some slight to moderate segregation was observed in the core samples retrieved from shaft 4. Compressive strength, Elastic Modulus, and unit weight testing were performed on selected samples from the cores obtained from these two shafts. The compressive strength testing indicated high variability in the values for both shafts. Between 1.5 to 3 m (5 to 10 ft) below the top of shaft 3, the compressive strength was considerably lower (some values were much less than the required 28 day strength) than the areas above and below. Lower compressive strength values were also observed for shaft 4 specimens results below 6.1 m (20 ft). The concrete specimens tested from this shaft exhibited a wide variability in the compressive strength. These depths correspond to the anomalous zones identified during the PISA CSL testing, suggesting compromised concrete condition. Shafts 3 and 4 are still undergoing evaluation with regard to the integrity of the shaft, its structural load carrying ability and subsequent actions if required.

SUMMARY AND CONCLUSIONS

The Pile Integrity Sonic Analyzer (PISA) represents the state-of-the-art equipment in deep foundations integrity testing. The system is lightweight and mobile, comprising of a generic laptop and modular equipment components. The PISA provides real time integrity evaluation and employs common operating systems (e.g. MS Windows), conforming to other requirements (i.e. graphics presentations and word processing). Allowing for easy software updates and hardware features, the PISA represents a new generation of NDT equipment that is better suited for versatile testing demands, advanced analyses and field applications.

A presented case history of detection and configuration of defects in large and complex rock socketed drilled shafts illustrates the importance of non-destructive testing and the success of the examined system. All four detected defects were confirmed to have construction problems. The two deep detected defects were found to be zones of voids and extensive segregated concrete that rendered the drilled shaft as incapable to carry load without a major repair. The shallower zones were found to be associated most likely with a problem in the construction technique. Though currently under investigation, the identified and delineated compromised zone appears to result in a defect that does not decrease the load carrying ability of the shaft below the design load.

APPENDIX 1

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