Application of Stress-Wave Theory to Piles, Niyama & Beim (eds) © 2000 Balkema, Rottendam, ISBN 90 5809 1503

Examination of a New Cross-Hole Sonic Logging System for Integrity Testing of Drilled Shafts

Samuel G. Paikowsky
Geotechnical Engineering Research Laboratory, University of Massachusetts – Lowell, Mass., USA

Les R. Chernauskas and Leo J. Hart
Geosciences Testing and Research Inc., North Chelmsford, Mass., 01863, USA

Carl D. Ealy and Albert F. DiMillio
Federal Highway Administration, McLean, Va., USA

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™ 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 different construction sites. The case history presented in this paper relates to a class 'A' prediction as tests were carried out on shafts in which defects were intentionally planted. The test results were submitted before the defects locations were known, both presented I the paper. The obtained results demonstrate the ease of use, accuracy of measurements and enhanced capabilities of the PISA. The systems' abilities are shown to be superior to any other currently available commercial system.

1 INTRODUCTION

Deep foundations integrity testing mostly applies to foundations constructed on-site from concrete or grout, such as drilled shafts, drilled mini piles, pressure-injected footings, and pre-cast 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.) common in these cast-in-place concrete piles. As a result of the increasing 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 a 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 advances, 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 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 recent case history including drilled shafts in which defects were intentionally fabricated.

2 OVERVIEW OF ULTRASONIC INTEGRITY TESTING METHODS

2.1 *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.

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 about 300 mm/sec (1 ft/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.

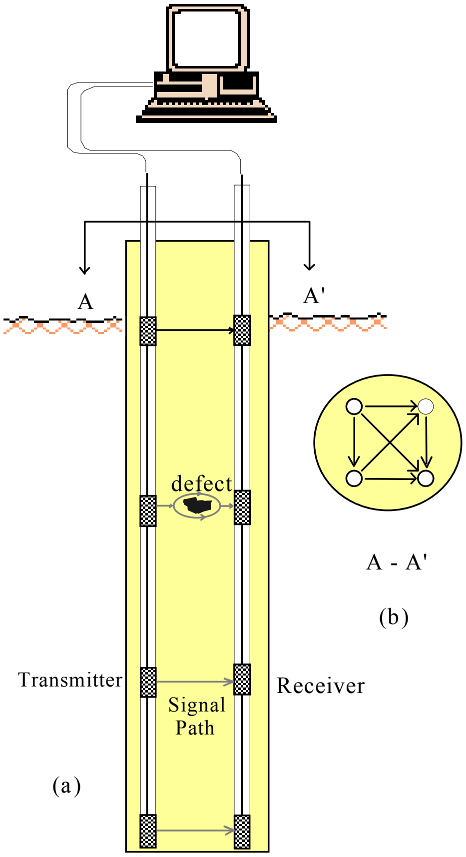


Figure 1. Typical CSL testing setup showing (a) transmitter and receiver at different depths, and (b) plan view of the CSL tubes with possible test combinations.

In homogeneous, good quality concrete, the stress/sound wave speed, C, is 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:

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

If for any reason the condition of the concrete is compromised, the wave speed will be reduced relative to that of the 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:

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

The wave speed in equation 2 is only an estimate, as the identification of the arrival time, t, is subjective and the distance between the tubes, L, is known only 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.

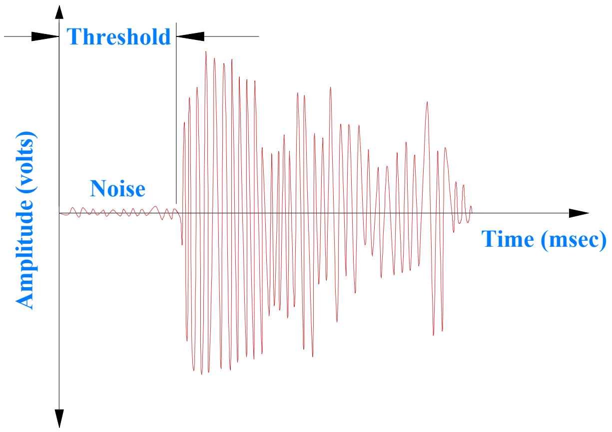


Figure 2. CSL typical testing signal.

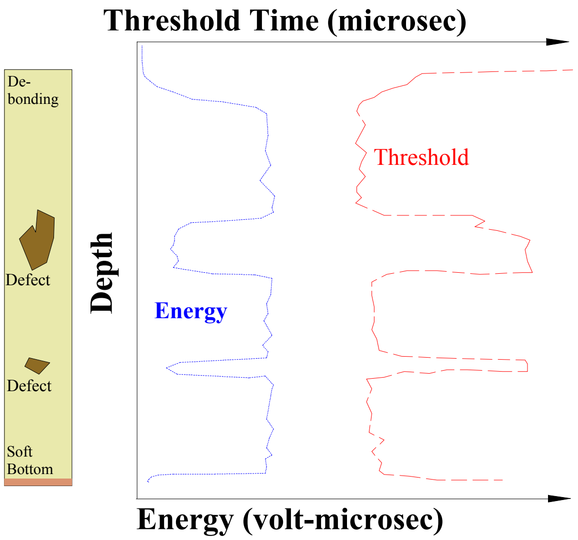


Figure 3 Presentations of CSL test results in the form of threshold time and energy with depth.

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.

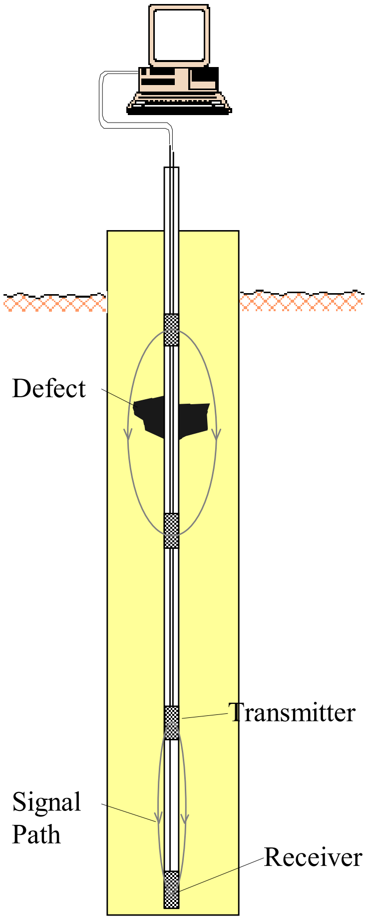


Figure 4. Typical SSL testing set-up showing transmitter and receiver at different depths.

2.2 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, 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). Recently 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 for the most efficient vertical placement of the tubes to assess the lateral integrity. Brettman and Frank (1996) describe a comparison between CSL and SSL tests.

3 THE PISA CSL/SSL TESTING SYSTEM

3.1 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 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.

Figure 5 presents a photograph of the PISA system, including computer and sensors. As a scale, the width of the computer screen is 23cm (9 inches). Figure 6 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. Real-time graphical presentation of the concrete integrity is provided during data collection. 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 7.

Figure 5. PISA system components.

4 CASE HISTORY

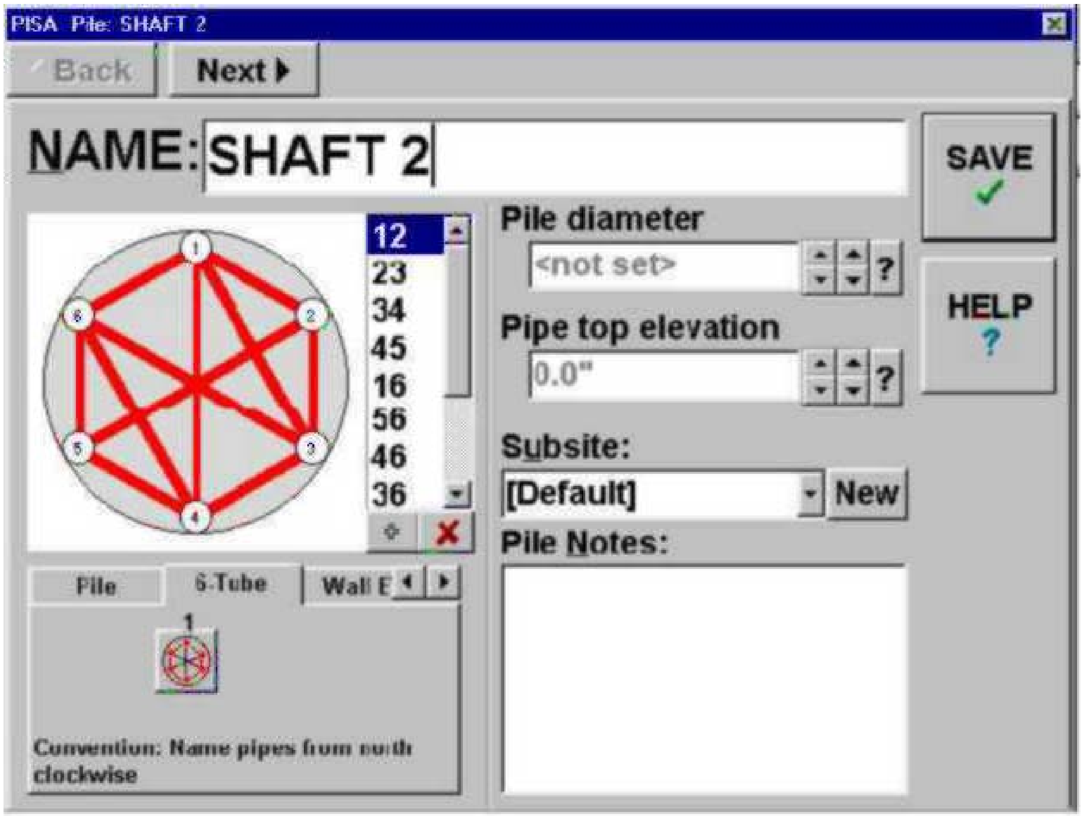
4.1 Background

Four drilled shafts were constructed at the Auburn University in Auburn, Alabama as part of a research study. The shafts are 914mm (36in) diameter and approximately 11.0m (36ft) long. Each shaft was equipped with 4 access tubes and various defects were installed during construction. The defects were constructed as soil inclusions formed by sand bags made of a tough material and tied to the rebar cage. The cross sectional area of the defect was based on the measured perimeter of the bags following their installation. The concrete was poured into a dry hole which was cased the full length of the shaft.

Over a year after construction, Geosciences Testing and Research, Inc. (GTR) personnel tested the shafts using the PISA system and submitted the results to Prof. Dan Brown of Auburn University. The actual "manufactured" defects were then revealed and comparisons were held between the predicted and actual defects.

4.2 Detected vs. Planned Defects

Figures 8 and 9 summarize the defects as detected by the PISA testing (on the right hand side) versus those planned/manufactured during construction (on the left hand side).



NAME: SHAFT 2

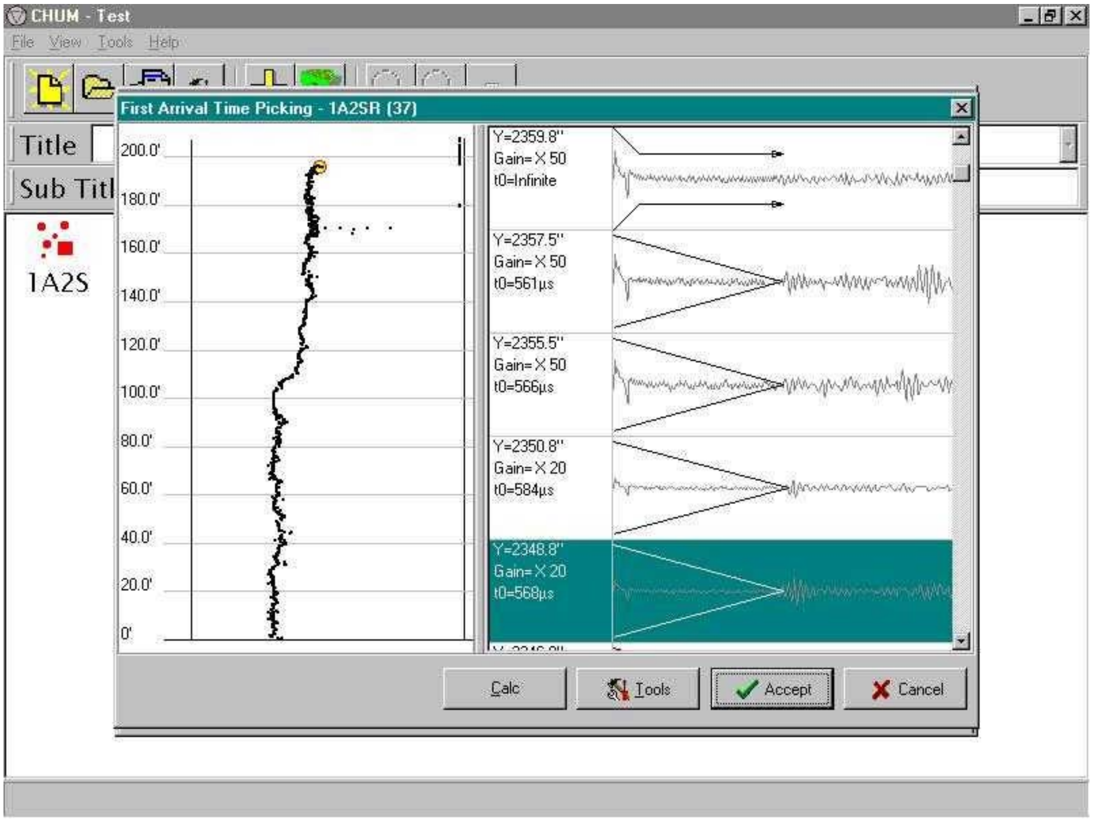
Pile diameter: <not set>

Pipe top elevation: 0.0"

Subsite: [Default]

Convention: Name pipes from north clockwise

Figure 6. Layout of the pile screen.



Y=2359.8"
Gain=X 50
t0=Infinite

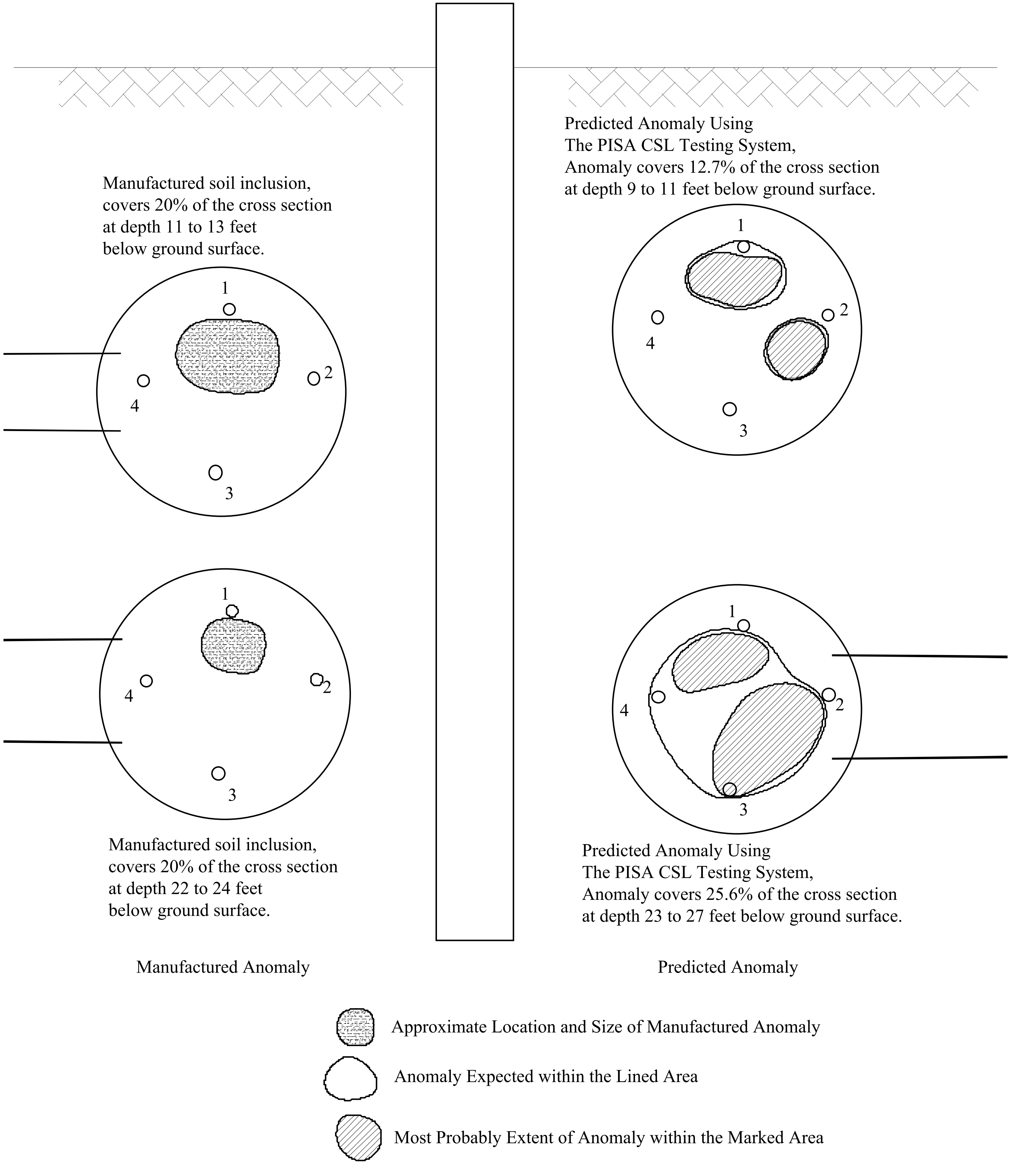
Y=2357.5"
Gain=X 50
t0=561µs

Y=2355.5"
Gain=X 50
t0=566µs

Y=2350.8"
Gain=X 20
t0=584µs

Y=2348.8"
Gain=X 20
t0=568µs

Figure 7. Data collection screen.



Predicted Anomaly Using
The PISA CSL Testing System,
Anomaly covers 12.7% of the cross section
at depth 9 to 11 feet below ground surface.

Manufactured soil inclusion,
covers 20% of the cross section
at depth 11 to 13 feet
below ground surface.

Manufactured soil inclusion,
covers 20% of the cross section
at depth 22 to 24 feet
below ground surface.

Predicted Anomaly Using
The PISA CSL Testing System,
Anomaly covers 25.6% of the cross section
at depth 23 to 27 feet below ground surface.

Manufactured Anomaly

Predicted Anomaly

Figure 8. Presentation of manufactured defects with predicted results of PISA CSL testing system for Shaft 4 at the Auburn University test site.

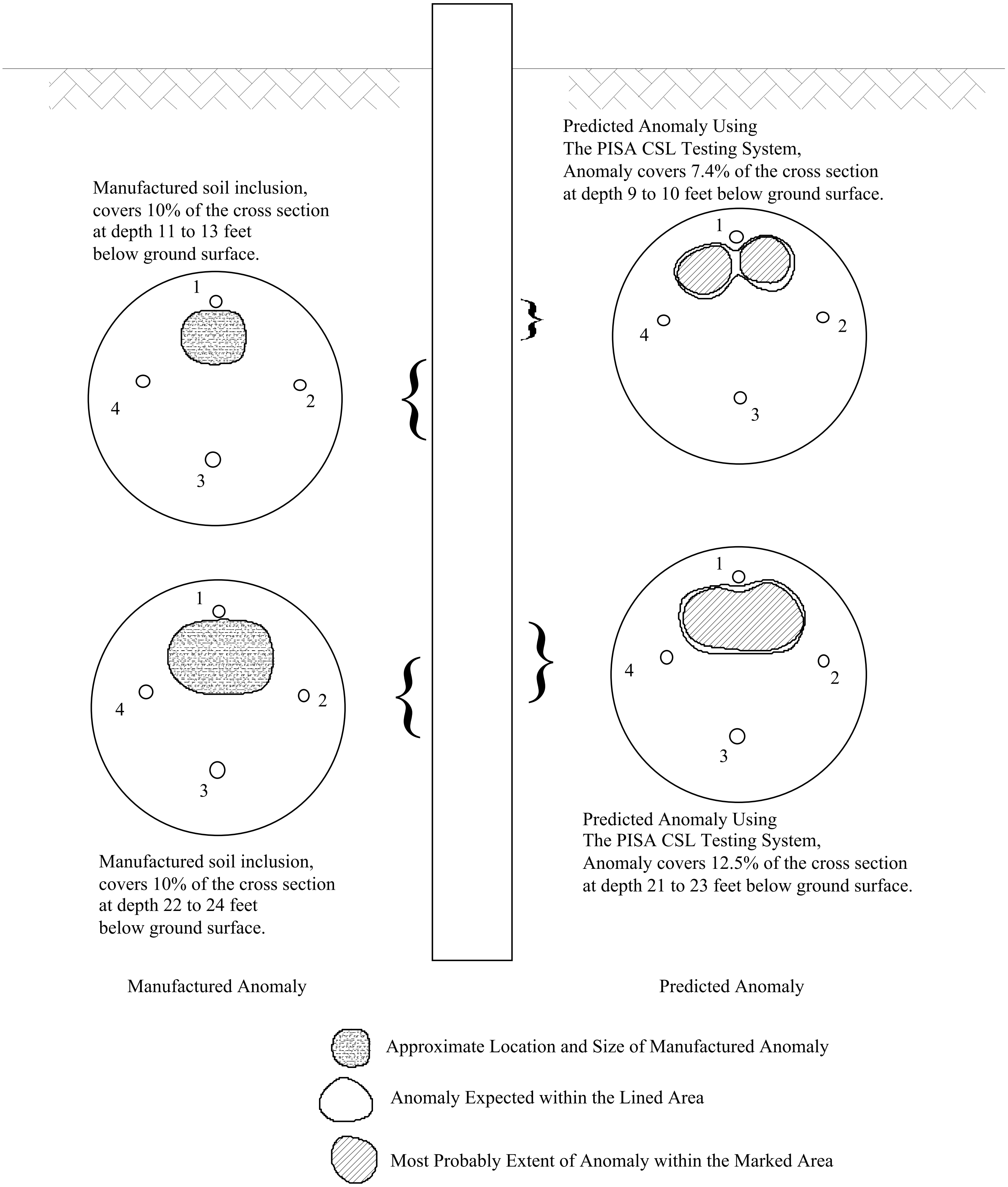


Figure 9. Presentation of manufactured defects with predicted results of PISA CSL testing system for Shaft 9 at the Auburn University test site.

The description of the manufactured defects were for example: "Shaft 4 - soil inclusion at 11 to 13ft below the ground surface on the north side (towards shaft 9), covers 20% of the cross-section." As such, the defects outlined in Figures 8 and 9 are a reasonable approximation of the descriptions.

Shaft 4: Two zones of defects were identified in shaft 4 (Figure 8). The center of the upper defect was suggested to be about 0.6m (2ft) above the center of the actual defect with overlapping margins. The area of the defects was correctly identified though the test suggested that it is concentrated in two zones which may be the case following the casting. The lower defect was identified in the right location, however was marked as approximately 25.6% of the cross-sectional area versus the manufactured defect planned as 10% of the cross-sectional area.

Shaft 9: Two zones of defects were identified in shaft 9 (Figure 9). The upper defect was identified as the right size but at a location approximately 0.6m (2ft) above the center of the actual location. The lower defect was identified at the right location and with the correct size.

Shaft 2: A soft bottom in part of the cross-section was identified in Shaft 2. This was not an intentional defect and may have resulted from the regular construction process.

Shaft 7: A weaker zone was identified between 1.5 to 3.7m (5 to 12ft) along one segment of the shaft (tube 2). No intended defect was installed in this shaft. The shaft, however, was laterally loaded to failure in bending and extensive tension cracks were expected to be developed on the south side around 3.7m (12ft). This information, like all other information, was provided after the tests results were submitted.

5 SUMMARY AND CONCLUSIONS

Four relatively small size sand inclusions were installed in two shafts out of four constructed shafts. All the defects were identified in the tests conducted over a year after construction. Three out of four defects were identified in their approximately correct size, the fourth defect was assumed to be about 3 times the size of the actual defect. Two of the defects were also identified within approximately 0.6m (2ft) of their actual locations.

Overall, the test results of Class 'A' prediction provided accurate and reliable evaluation. The tomography feature of the testing equipment certainly allows an operator to estimate the extent of the defected zone with a higher accuracy than ever before.

The challenge of finding the defect seems to be smaller than its accurate description. The latter, however, is of great importance in order to be able to conduct structural evaluation of the defected shaft and hence to assess the need of remedial action.

In summary, the PISA system represents a new generation of CSL equipment capable of conducting non-destructive testing with ease and accuracy not available before.

ACKNOWLEDEMENTS

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