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Non-Destructive Testing of Piles: An Experimental Study

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Abstract. Construction of Deep Foundations is in practice in India since years now and state of art design and construction techniques are being followed by practicing engineers for design of reinforced concrete and steel piles; both driven and bored. However, the quality control check of these underground structures is still in development stages and several destructive, partially destructive and non-destructive tests are in various stages of developed and experiment. This paper presents an experimental study to determine the quality of piles based on non-destructive methods; Low-strain pulse echo method and cross-hole sonic logging method. These two methods have recently gain wide acceptance as quality control procedure for piles in India being not only cost effective, but also provides reliable near accurate results if analyzed properly. To study the quality of piles, two bored reinforced concrete piles have been cast at proximate location using same construction techniques; one without any defect and one with known defects at known locations; and an attempt has been made to find the known defect with use of non-destructive tests. The paper discusses findings of two testing methods (Low-strain pulse echo and cross-hole sonic logging) in detail and presents the effectiveness, analyzing techniques and limitations of both the methods.

Keywords: Non-Destructive Testing; Low-strain pulse echo method; Cross-hole sonic logging method

1 Introduction

In India, bored pile construction has been used for many years, and professional engineers have a good understanding of how to build high-quality piles with various depths and diameters in accordance with project specifications. However, just like other civil engineering elements, bored piles require a thorough quality control procedure, and non-destructive testing is essential to achieve this objective.

Cast in-situ bored pile quality assessment is a challenging task that entails assessing the strength of the pile material as well as potential defects in the pile shaft. Because only the top of a pile foundation is accessible, they present a special challenge for non-destructive testing. To ensure the reliability and durability of the design, meticulous adherence to the concrete quality of the design strength is necessary.

The paper discusses findings of two non-destructive testing methods (Low-strain pulse echo and cross-hole sonic logging) in detail and presents the effectiveness, analyzing techniques and limitations of both the methods.

2 Piles casted for experimental study

Two bored reinforced concrete piles have been cast at proximate location using same construction techniques; one without any defect and one with known defects at known locations.

2.1 Pile casted without defects

Pile P01, a reinforced concrete pile with a 600mm diameter hole, was constructed with meticulous quality control. The pile is 8000mm deep. As access tubes for cross-hole sonic logging, four numbers of hollow MS piles with a 60mm diameter were fastened to the reinforcement during casting. Cross-section of the pile is shown in the Figure 1.

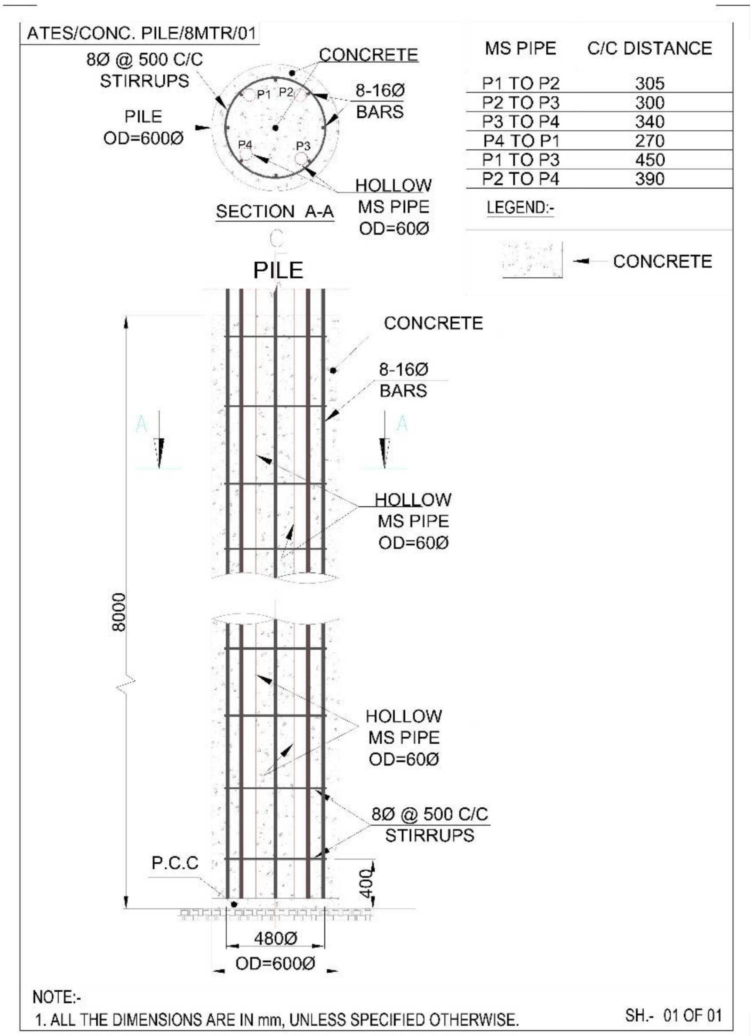


Fig. 1. Cross-section of Pile 01 casted for experimental study without defects

2.2 Pile casted with known defects

Defects were purposefully included during the casting process in the second pile that was casted for the experiment. Pile P02 is a 600mm diameter reinforced concrete pile and is 6000mm deep. In place of concrete, a 500mm thick zone of earth was filled at a depth of 1500mm from the toe of the pile, and a 200mm diameter hollow MS pipe with a 500mm length was also buried in the pile's core. Additionally, during the casting process, four hollow MS piles with a 60mm diameter were fastened to the reinforcement as access tubes for cross-hole sonic logging. The pile was also instrumented with sensors for other studies. Cross-section of the pile is shown in the Figure 2.

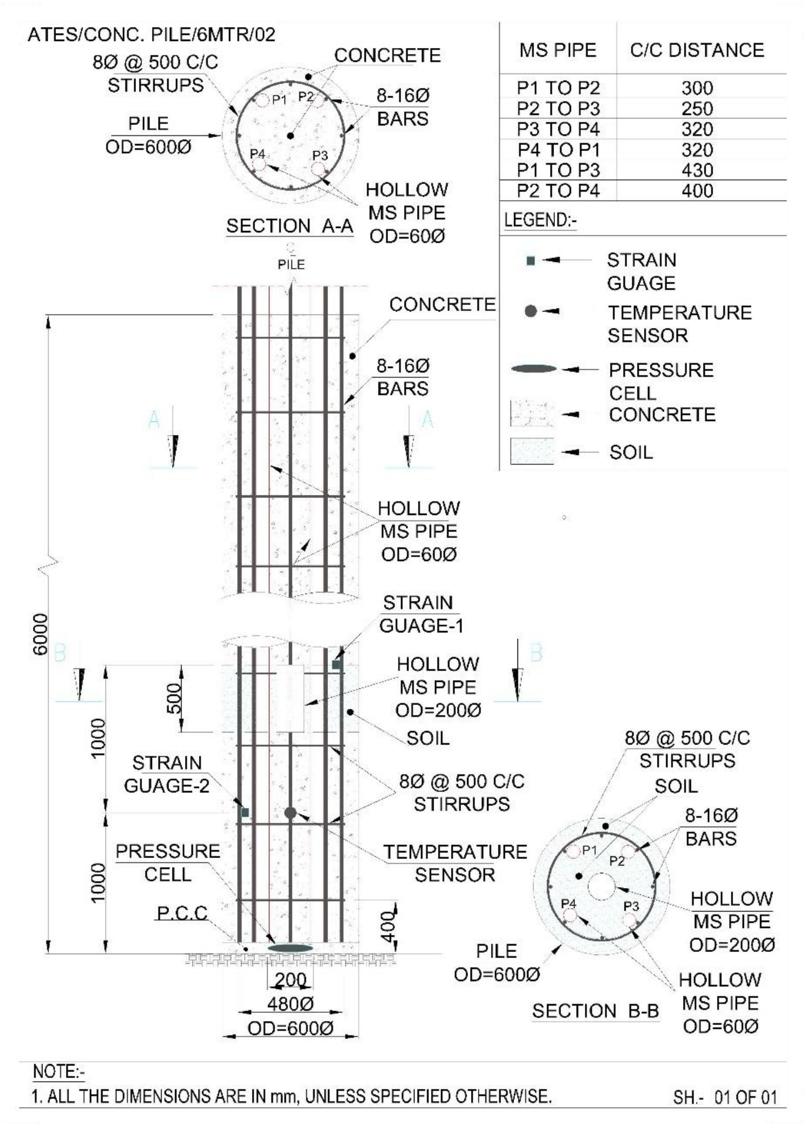


Fig. 2. Cross-section of Pile 02 casted for experimental study with known defects

3 Non-Destructive Testing of Piles

Non-destructive testing provides practical, efficient, and reliable quality control techniques that are applied in the field to ensure the cast quality of site-bored piles, therefore lowering the risks associated with piling foundations. In this work, the low-strain pulse echo method and the cross-hole sonic logging method have both been employed to identify the faults that were purposefully included into the pile cast. The limitations of both methods are then discussed.

3.1 Low-Strain Pulse Echo Method

The Low Strain Pulse Echo technique is a non-destructive method used for testing of concrete piles; the methods are based on one-dimensional stress waves. The technique is being effectively used for concrete and steel pile quality checking in several regions of the world. Due to the procedure's ease of use and speed, several piles may be examined in a single working day without affecting site operations. In India the test is done mainly in accordance with Indian standard [3] with reference to [1] wherever appropriate. The testing process is succinctly given below [3]. Figure 4 shows the schematic diagram of the apparatus and Figure 5 shows the PDI make instrument.

The pile is lightly tapped with a tiny metal/hard rubber hammer, which sends a downward-moving stress wave into the pile. In an ideal situation, the shock would travel down the length of the pile, reflect off the toe due to soil resistance, material section, density, and resistance changes, and be recorded using a suitable transducer/accelerometer (also held on top of the pile near the point of impact) for post processing. But if the pile contains any irregularities, breaks, or flaws along its length, these will create secondary reflections that will be added to the return signal but arrive at the receiver before the primary wave, which is reflected off the toe. This early occurrence of a stress wave indicates that there is a pile imperfection (Figure 3).

An expert can detect the sort of faults, such as necking or buckling, by carefully analyzing the acquired signal and having knowledge of the ground's conditions, the age of the concrete, etc. The reflected stress waves are monitored by processing techniques. The detected signals are amplified and translated into digital display as velocity versus length or frequency versus mobility records, providing information on the structural integrity of piles.

The integrity testing's inputs include the stress wave velocity and rough pile depths. The pile concrete's mass density and young's modulus affect the stress wave velocity. Stress in a pile is represented by 1-Dimensional Wave Theory. The pile top force and velocity measurements may be used to evaluate these stress waves. PIT recognizes variations in the pile's impedance (Z). Impedance of the pile is directly related to the stiffness of the pile.

$$Z = \frac{EA}{c} \tag{1}$$

Where, Z = Impedance, A= Cross sectional area of pile, E = Young’s modulus of Pile, c = Wave speed of pile material. Impedance thus takes into consideration both material qualities and cross-sectional change. The PIT apparatus, which consists of a hammer, a motion sensor, and a processing unit, is relatively small and easily transportable. The weight of the hammer ranges from roughly 1 to 10 lbs. To quantify the applied force, the hammer may occasionally be equipped with a pressure sensor or strain gauge. An accelerometer often makes up a motion sensor. The processor saves and examines the signals that were captured. [8]

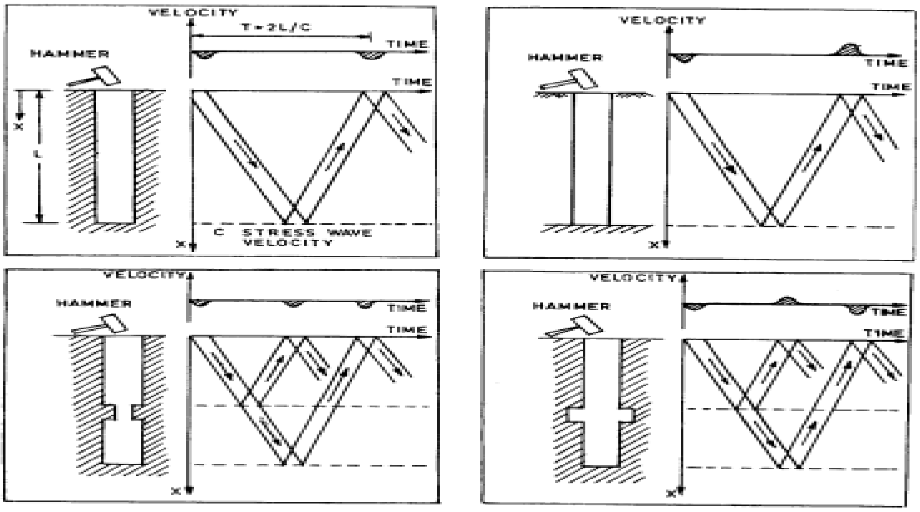


Fig. 3. Pattern of Stress Wave reflection [3]

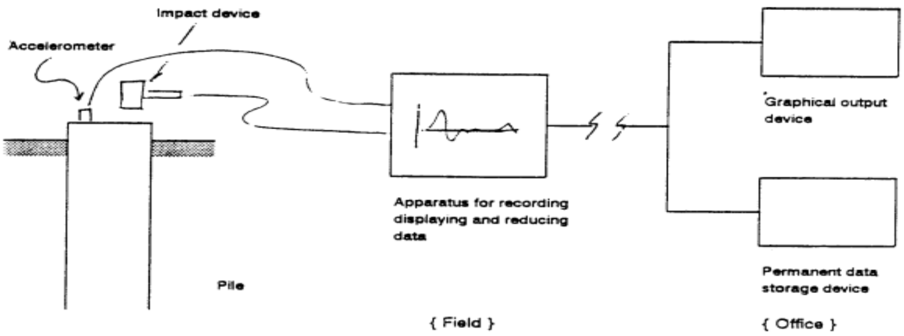


Fig. 4. Schematic Diagram of Apparatus for Integrity Testing [1]

Fig. 5. PIT Instrument (PDI)

Analysis and Interpretation. In Figure 6(a) clear pile toe reflection can be seen without intermediate waves and therefore, there are no defects in the pile. In Figure 6(b) clear pile toe reflection can be seen along with positive then negative wave in the middle indicating necking or reduction in concrete area in the middle of the pile. Negative wave followed by positive wave indicates bulging or increase in area of concrete pile. In Figure 6(c) the wave is going up and down multiple times from the starting indicating defects near the top of the pile.

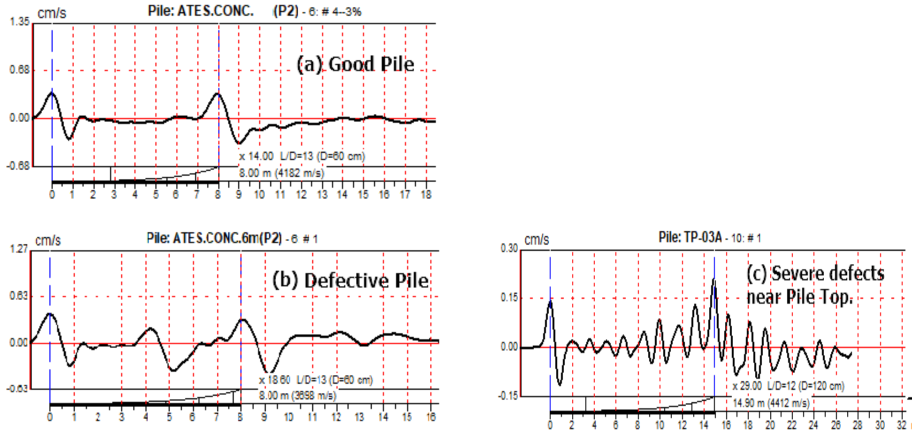


Fig. 6. PIT Graphs Interpretation

The need to add improvement to field data arises from the possibility of noise. Random noise is most readily reduced when PIT data is collected on-site by averaging many recordings. According to [3], testing must be performed at five to six locations to cover the full stretch of pile diameter.

3.2 Cross Hole Sonic Logging Testing Method (CSL)

An NDT technique Cross-Hole Sonic Logging (CSL) involves transmitting an ultrasonic signal via the shaft between two parallel access tubes filled with water. Separate access tubes are used to drop a transmitter probe and a receiver probe to the shaft's bottom. As the probes are elevated to the top of the shaft, measurements of the signal transmission are gathered. According to [12] & [6], a shaft should include at least one tube for every 0.3m of shaft diameter, ideally with a minimum of four tubes. In India the Cross-hole Sonic Logging (CSL) is conducted according to the specifications of [2].

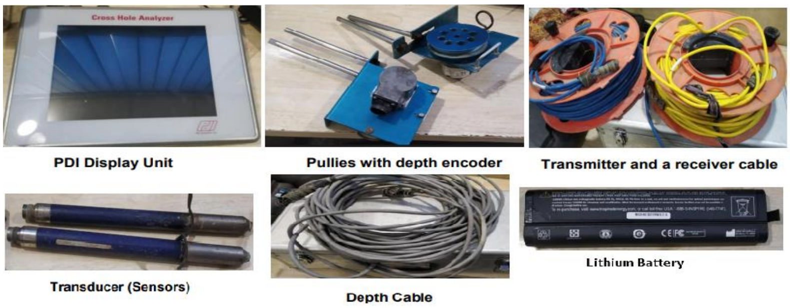


Fig. 7. Cross Hole Analyzer System manufactured by PDI

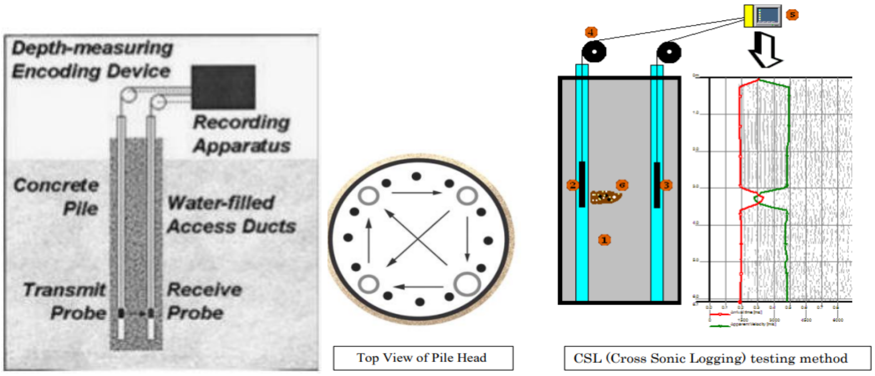


Fig. 8. Cross Hole Sonic Logging Methodology

Analysis and Interpretation. Pile quality quantitative assessments based on CSL measurements frequently entail judgement and expertise. An ultrasonic pulse's relative energy and first arrival time (FAT) between parallel access tubes set up in the deep foundation are measured throughout the test. During testing, it's crucial to keep the water level at the top and ensure that there is no air gap. A constant FAT and signal energy over the whole length of the pile denotes a consistent level of concrete quality (Fig. 9(a)). Any abnormality, such as a soil inclusion or low-grade concrete, will result in an increase in FAT or a decrease in relative signal energy, or both (Fig. 9(b)). The presence of anomalies or deteriorating concrete at that point is therefore indicated by a rise in FAT, a decrease in signal intensity, or both. The CSL results lead to the following conclusions.

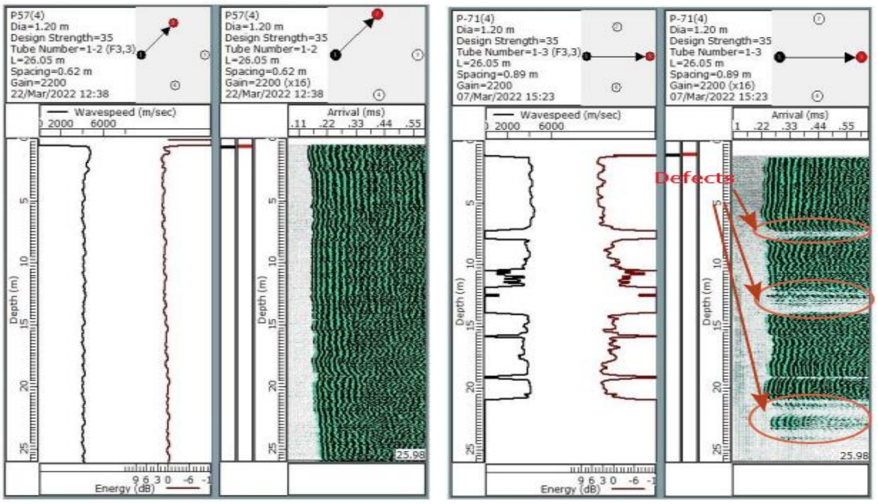
The vertical display of First Arrival Time (FAT), wave speed, energy, or waterfall graphic makes it simple to determine the vertical extent of a concrete quality change.

From the several profiles displaying the same flaw, the horizontal extent of a defect or the percentage of cross-sectional area damaged must be determined. Offsetting the probes vertically and redoing the test may assist to pinpoint the defect's horizontal location if it only affects a few tube profiles.

The relative FAT rise is often used to determine the degree of a change in concrete quality. but in a more qualitative than quantitative way, and appraisal of the Relative energy. The scale in Table 1 can be used to assess the integrity of a pile.

Table 1. Scale for Pile Integrity as per CSL results [6]

Concrete Quality	FAT Increase	And/or	Energy Reduction
Good (G)	0 to 10%	And	Less than 6db
Questionable (Q)	10 to 20%	And	Less than 9db
Poor/Flaw (P/F)	21 to 30%	Or	9 to 12 db
Poor/Defect (P/D)	More than 31%	Or	More than 12 db



(a) Good Pile (b) Defective Pile

Fig. 9. Cross Hole Sonic Logging Interpretation

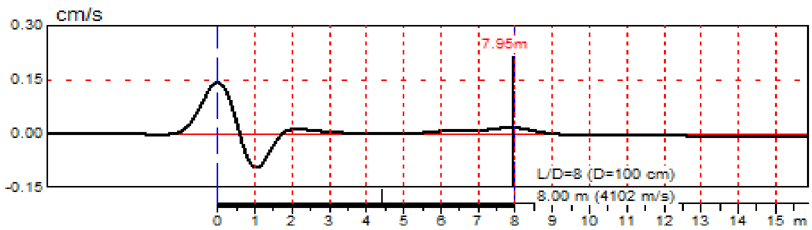
4 Test Results and Interpretation

4.1 PIT results

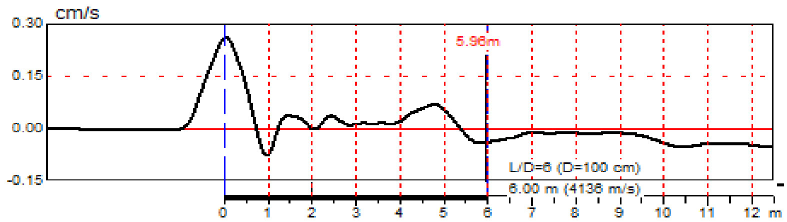
Six numbers of test were performed on top of both piles and results are presented below.

Pile P01. Figure 10(a) shows the PIT result on Pile P01. At a depth of 7.95m, a toe reflection is visible. The earth around the pile may dampen the signal as it descends while field data is being collected, this toe reflection can be enhanced using a suitable Magnification Factor (MA) in the analysis software. This pile has no defects and a toe at depth 7.95m.

Pile P02. Figure 10(b) shows the PIT result on Pile P02. At a depth of 4.5m a significant positive wave is visible followed by a negative wave. This clearly indicates a reduction in the concrete area. This aligns with the location of defect that was intentionally created in the pile P02 thus confirming the effectiveness of the test to detect abnormalities.



(a)



(b)

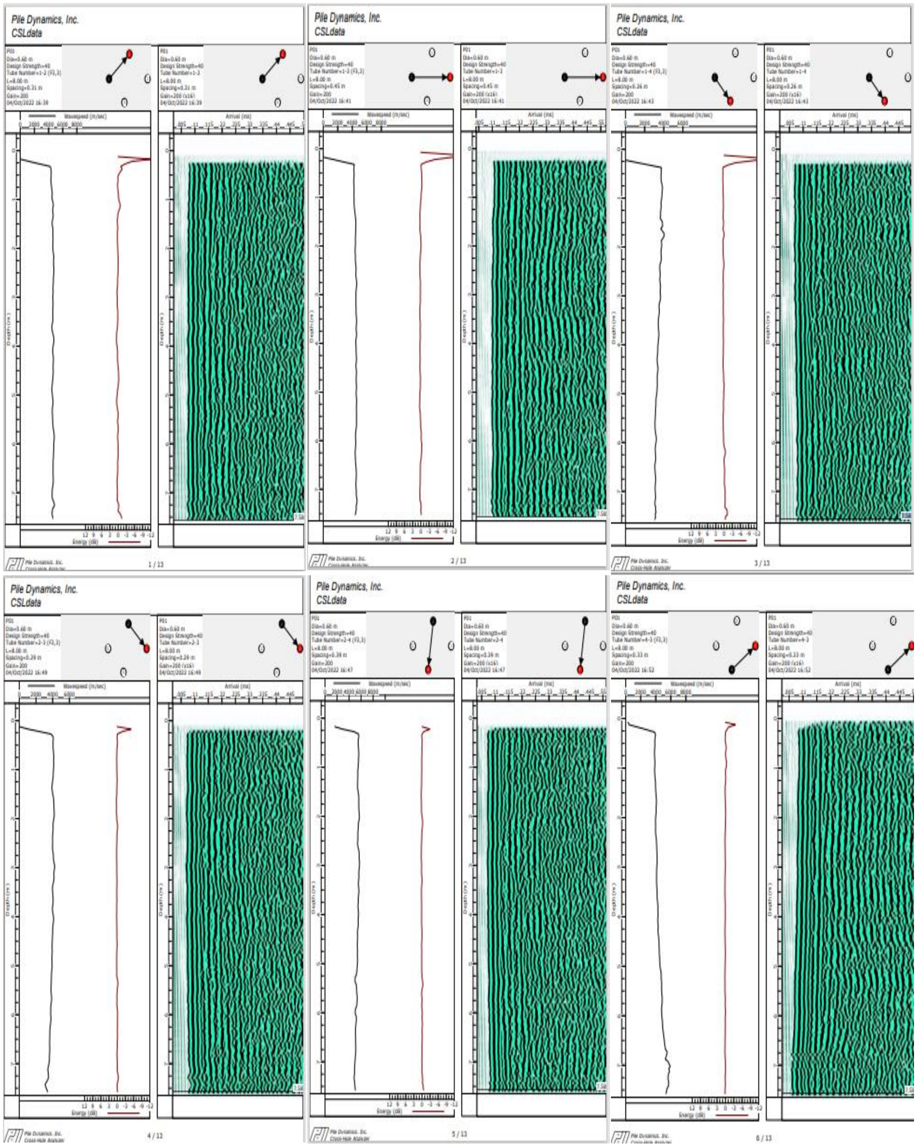
Fig. 10. PIT test result output on Pile P01 and P02

4.2 CSL results

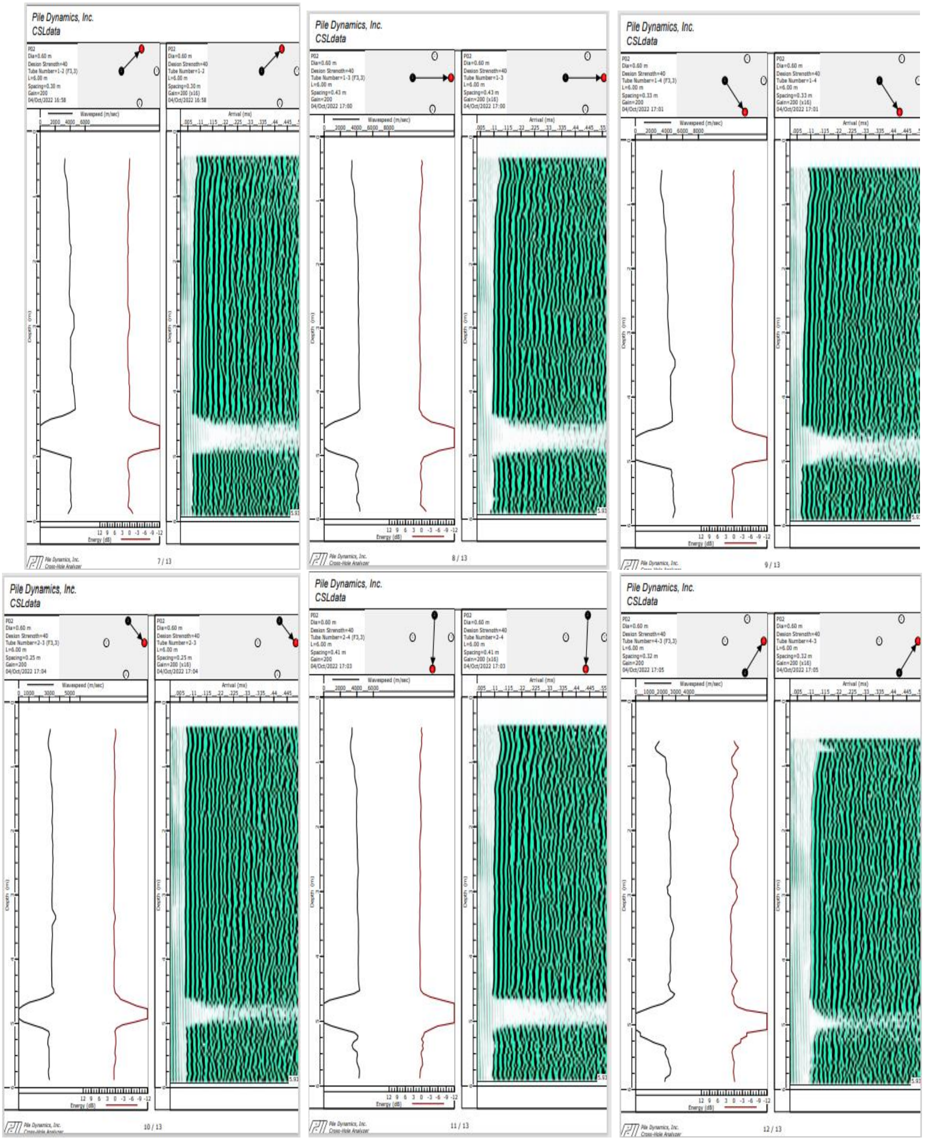
Six numbers of test were performed in the 4 access tubes placed. Testing configuration was MS Pipe P1-P2, P2-P3, P3-P4, P4-P1, P1-P3 and P2-P4 (refer cross-section of the piles in Figure 1 and 2).

Pile P01. Figure 11(a) shows the CSL results of all six configurations on Pile P01. A constant FAT and signal energy over the whole length of the pile is noted denoting a consistent level of concrete quality.

Pile P02. Figure 10(b) shows the CSL result on Pile P02. At a depth of 4.5m to 5m, increase in FAT and a decrease in relative signal energy is noted. Decrease in energy signal is higher than 12 db denoting very poor concrete which is consistent with the defect as there is no concrete at that location. Further, carefully looking at the waterfall diagrams along the diagonal with that of the results along the periphery, it can be noted that the quality of the pile degrades at the center. This is consistent with the hollow area defect of the pile thus confirming the effectiveness of the test to detect abnormalities.



(a)



(b)

Fig. 11. CSL test result output on Pile P01 and P02

5 Conclusion

While PIT can assess the whole cross section as well as the profile of the shaft, CSL can only assess the concrete in between access tubes. PIT simply reveals the depth and only provides a very approximate estimate of the size of a defect, whereas CSL can estimate the depth, horizontal location, and extent of a defect. CSL is efficient in locating a "soft toe" Low Strain Integrity Testing, whereas. Both methods cannot determine the cause or material properties of a defect. The combined test results offer a more thorough examination of the shaft than any test performed alone. For instance, if CSL data show no FAT delays or energy decreases at the equivalent depth but PIT testing shows an impedance drop there, it is likely that the impedance decrease reported there is due to a reduction in cross section rather than a problem with the material's quality.

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