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Article

Comparative study of pile quality control techniques

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Abstract. This article delves into the critical realm of quality control in pile foundation construction, presenting a comprehensive exploration of both destructive and non-destructive testing methodologies. Focused on enhancing structural integrity and reliability, the study evaluates techniques such as concrete strength testing, core sampling, Cross-Hole Sonic Logging (CSL), and Pile Integrity Testing (PIT). Results from field observations conducted during construction of the Light Rail Transit (LRT) system in Astana showcase the effectiveness of non-destructive methods, with 1,896 bored piles subjected to rapid testing. Significant findings reveal that approximately 75% of tested shafts exhibited anomalies, emphasizing the necessity for meticulous quality control. The article concludes by advocating for the adoption of advanced quality assurance protocols to mitigate risks and ensure the robustness of pile foundations in construction projects.

Keywords: pile foundations, quality control, non-destructive testing, structural integrity, reliability.

1. Introduction

Pile foundations constitute a vital aspect of construction projects, determining the structural integrity and longevity of buildings or structures [1]. Post-installation, a proportion of piles commonly exhibit defects stemming from manufacturing or transportation processes [2]. Various factors, such as inadequate concrete volume during concreting, interruptions in the concreting process, or compromised casing joints, can compromise the integrity of bored-injection piles [3]. Similarly, driven piles may incur defects due to safety breaches during transport or installation, subpar joint quality in composite piles, or concealed flaws in pile shaft fabrication. Consequently, factory defects in piles can render them unusable, leading to compromised integrity and reduced bearing capacity, affecting both soil and material. Such issues are prevalent across diverse pile construction methodologies, including bored, bored-injected, driven, or indentation piles. Despite the significance of pile quality control, it often receives cursory treatment, limited to maintaining records and concrete sampling at delivery [4]. However, such measures offer only indirect assessment, focusing on compliance with design specifications rather than manufacturing quality or shaft integrity. Consequently, there's a pressing need for a more robust quality control framework tailored to pile construction. Traditional testing methods, like static and dynamic load tests, while representative, only assess pile bearing capacity and fail to ensure reinforced concrete structure quality [5]. Direct quality control during drilling and concreting at construction sites often proves inadequate, lacking comprehensive operation-by-operation oversight. Hence, modern pile quality control techniques warrant investigation to address these shortcomings and enhance construction practices. This study aims to explore the effectiveness of contemporary pile quality control methodologies.

2. Methods

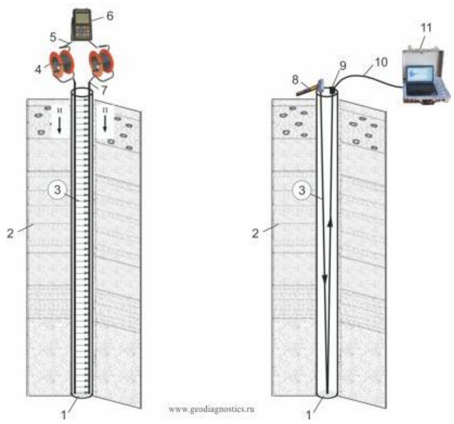
2.1 Destructive method of pile quality control

Concrete strength control for bored and driven piles follows [6], involving sampling from randomly selected mixes per [7], with at least two samples per batch and one per day. [8] guides sample preparation in verified moulds [9]. Testing yields an act indicating concrete strength. Samples should ideally cure in conditions mimicking structure hardening, but often cure externally, differing from borehole conditions. Hence, core samples drilled from pile shafts offer more representative results. Quality control includes strength testing of vertically drilled core samples at 0.5 m intervals. Sampling, overseen by the author, uses a small rotary drilling rig. Cores are labeled with details such as pile number, absolute mark, diameter, depth, and date. Quality control entails testing a minimum of two piles out of one hundred, increasing if defects are found. However, this method is destructive, labor-intensive, and costly, making comprehensive implementation impractical.

2.2 Non-destructive methods of pile quality control

Meanwhile, piles as responsible structures, the quality of which depends on the reliability of operation of the building (structure), must be subjected to continuous control. In contrast to destructive, the non-destructive methods are used for continuous control (Figure 1). Seismoacoustic (sound) and ultrasonic techniques are employed for assessing pile lengths, pinpointing defects like cracks and weakened sections, and evaluating the mechanical properties of pile concrete. Utilization of seismoacoustic and ultrasonic devices involves two main phases: conducting on-site pile tests and analyzing the acquired data with specialized software tools [10].

a) Destructive method



b) Non-destructive method

c) Cross-Hole-Analyzer (CHA)

d) Seismoacoustic and ultrasonic methods

Figure 1 – Pile quality control methods

2.3 Cross-Hole-Analyzer (CHA)

CHA uses a cross-hole acoustic survey method to determine the quality and consistency of concrete between pairs of PVC or steel pipes pre-installed in bored shafts, cast-in-place walls, bored piles, cast-in-place piles or other types of concrete foundations (Figure 2). The transmitter and receiver are in different conductive tubes, and it is important that they are at the same level when scanning. For these tests, the conductive holes are formed in advance using two steel or plastic tubes. Defects that are between the tubes are well defined, but since there is no radial scanning, there is a "dead zone" outside the tubes where defects cannot be detected. The main body of the pile can be examined using the required number of tubes (Figure 2).

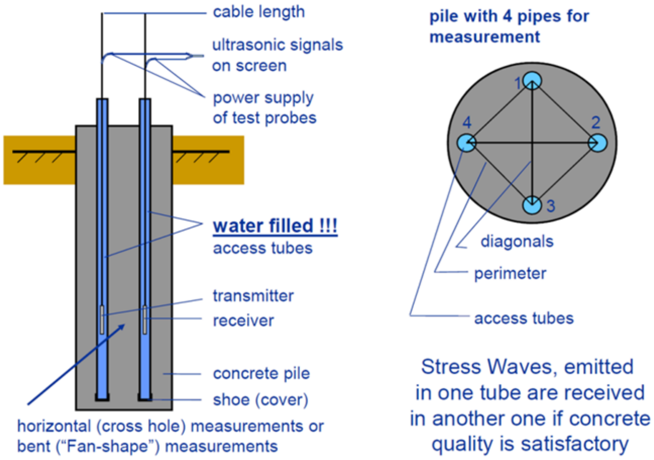


Figure 2 – Cross-Hole Sonic Logging principle

The number of conductive tubes increases significantly with the pile diameter (Figure 3).

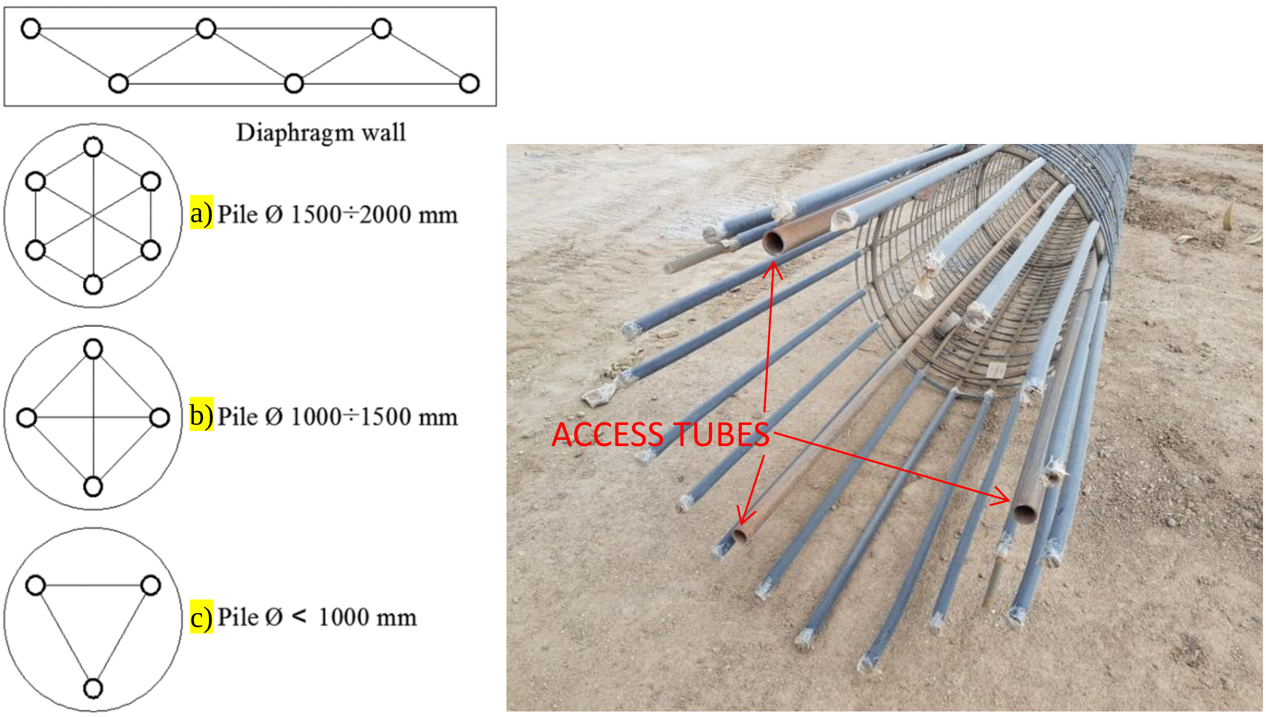


Figure 3 – Typical access tube configurations: a) scanning along three measurement directions; b) scanning along the perimeter and diagonals (six measurement directions).

The test cost correlates with the expense of constructing the conductive tubes. Discrepancies in concrete continuity or uniformity, typically on a decimeter scale, are identified through alterations in wave velocity or energy absorption, as illustrated in Figure 4.

2.4 Seismoacoustic method and ultrasonic method

Pile Integrity Tester (PIT). PIT performs integrity testing under small deformations according to also called acoustic echo testing. The PIT can be used for bored piles, bored shafts, driven piles, driven concrete pipes. It detects potentially dangerous defects such as significant cracks, neck formation, soil inclusions or cavities and, in some cases, can identify unknown dimensions of existing piles or test piles supporting existing bridges or abutments. Non-destructive quality control of pile continuity is based on the principle of acoustic flaw detection - the analysis of the passage and reflection in the structure (piles) under investigation of an acoustic wave, which is initiated by a calibrated impact on the pile head. The tests are carried out in accordance with ASTM D5882-16. The impact is produced by a special hammer with predetermined impact pulse parameters sufficient to dynamically excite the pile. The work also makes use of highly sensitive accelerometer sensors mounted on the pile head, as well as a separate analogue-digital instrument that includes a computer with a display and software that processes the information from the accelerometers. The resulting impact disturbance, modeled as a random uniaxial longitudinal compression wave, enters the pile body. A reflected wave is generated from the bottom of the pile and from defects in the pile, such as fractures, voids or cross-sectional inhomogeneity's, propagating in the opposite direction to the source of the original wave. To ensure the reception and registration of the secondary wave in piles, the removal (cutting down) of low-quality concrete is carried out beforehand, followed by leveling the surfaces of the pile caps for the installation of accelerometer sensors. The level of the surfaces of the pile caps after leveling should be horizontal. In order to increase the reliability of information on the results of pile testing, measurements are carried out at least at 3 different points of the pile caps. The measurement points (impact load applications) must be distributed evenly over the area of the caps. The accumulated signals are recorded in the computer memory for further processing and analysis. Figure 4 shows a graph of wave propagation in a rod with a weakened cross-section. An example of a narrowed cross-section of a bored pile. Processing, decoding and interpretation of low-frequency wave signals obtained during continuity testing of piles should be performed by a qualified specialist using special software.

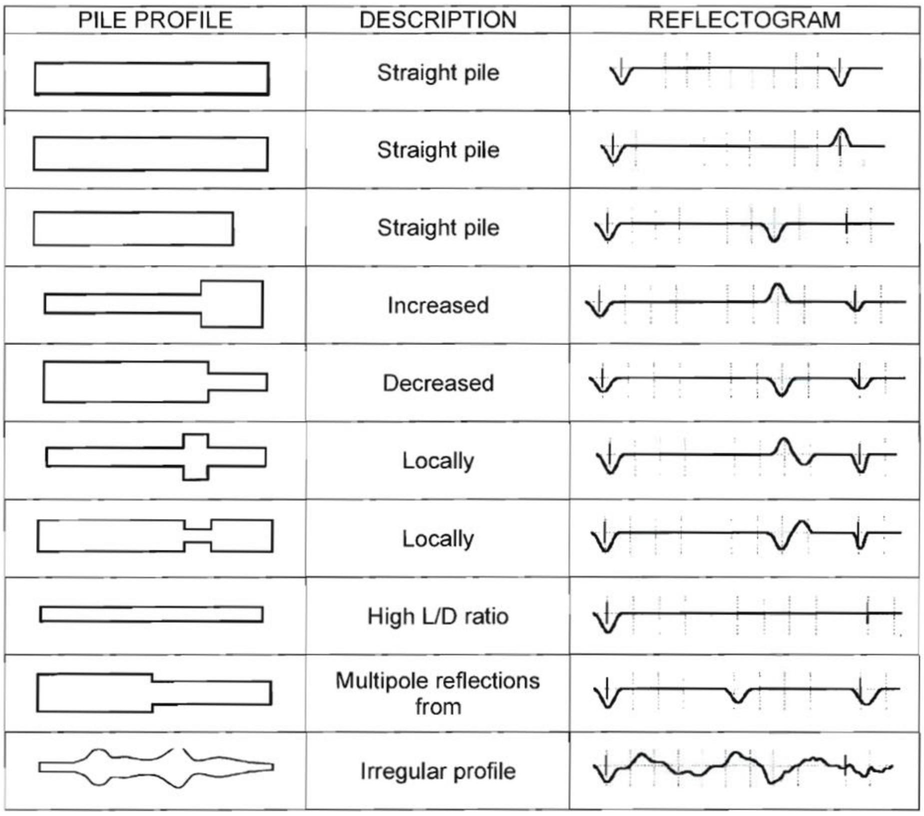


Figure 4 – Typical pile profiles with respective reflectograms

The pile continuity testing method relies on the principles of sound wave propagation, encompassing both high and low frequencies, within solid materials. It stands as one of the most contemporary techniques employed in global pile testing practices in recent years. This method facilitates comprehensive analysis of pile continuity across all pile types and enables the detection of structural defects within the pile body. Depending on the estimated velocity of plane wave propagation in concrete, this method allows for various determinations, including:

1) The approximate length of the piles;
2) Widening in the cross-section of the piles;
3) Narrowing in the cross-section of the piles;
4) Change in soil layers;
5) Change in pile material;
6) Transverse cracks in the pile shaft;
7) Inclusions of foreign material.

Various devices are used for ultrasonic pile testing: IDS-1 (Russia); Pocket Echo Tester and Pile Echo Tester (UK); Pile Integrity Tester-PIT (USA); and Sonic Integrity Tester-SIT (Netherlands).

Currently in Astana city works on construction of LRT (Light Rail Transit) public transport system are underway. Construction works are carried out by the Chinese company "China Railway Asia-Europe Construction Investment Co". Testing of bored piles by Pile Integrity Testing (PIT) and Cross-hole Sonic Logging (CSL) methods at the construction site of the object: "New transport system of Astana city. LRT", (section from the airport to the new railway station) was carried out with technical and financial support of L.N. Gumilev ENU and KGS LLP with the participation of the author. The tests were conducted at the LRT construction site in Astana. Nowadays non-destructive methods have become an effective technique to check the integrity of concrete deep foundations. The results of non-destructive tests carried out using rapid methods technology on bored piles located at 18 stations and interchanges were analysed. A total of 1,896 bored piles were tested between February and October 2018 [11]. During the production of bored piles, there is a risk of cavities and other defects. For example, soil particles may get into the concrete mix. To detect defects, the integrity of the bored pile is examined (Figure 5).

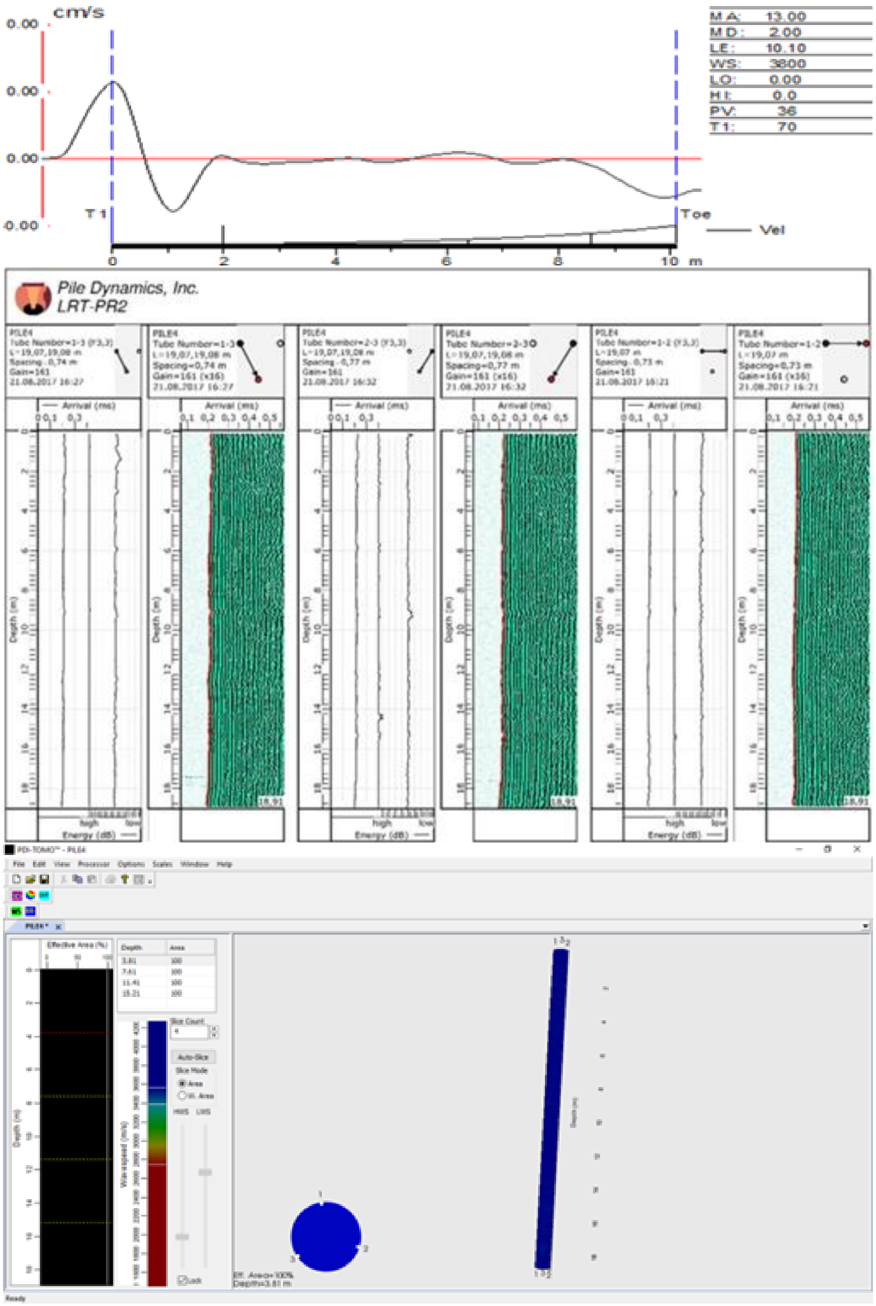
Figure 5 – CSL pile testing with two probes

3 Results and Discussion

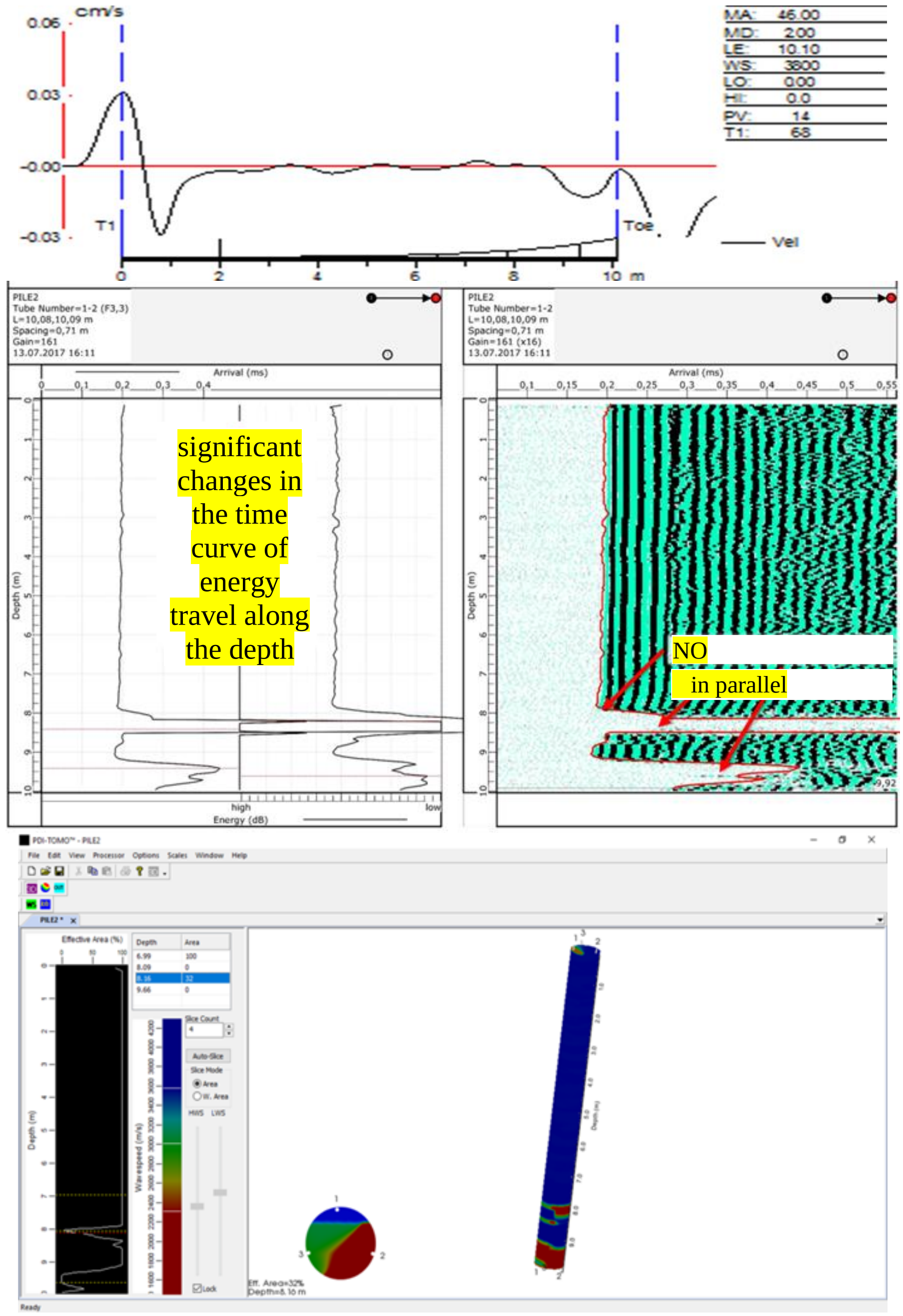
Reinforced concrete piles are frequently utilized as a substitute for deep foundations, especially in challenging soil conditions or where vibration from pile driving is unsuitable. Despite the implementation of quality control measures during initial foundation installation, validating the integrity of drilled shafts during construction, particularly in damp conditions, remains challenging. [12] observed that in over 400 drilled shafts tested across multiple projects in South Carolina, roughly 75% exhibited anomalies, with more than 30% of all shafts containing at least one anomaly. Bored shafts typically bear higher design loads than driven piles, resulting in lower repeatability, as highlighted by the findings of [13]. Given the elevated likelihood of anomalies in drilled shafts and their diminished repeatability, ensuring the quality of each drilled shaft holds paramount importance for every pile [14-15].

There is a set of rules according to which the quality control of bored pile production is determined. The CSL method of pile integrity inspection is considered to be the most effective. The physics of the process is that the speed of propagation of the sound wave changes depending on the structure of the material and its physical and mechanical properties.

The signal is recorded and compared to a reference signal. The difference in the signals characterizes the condition of the material in the piles (see Figure 6).



a) Results of "good" piles



b) Results of "bad" piles

Figure 6 – The tests were carried out at the LRT construction site in Astana

Low Strain Testing constraints:

- Detectable: Pile length, inclusions of foreign material with different acoustic properties, cracking perpendicular to the axis, joints and staged concreting, abrupt changes in cross section, distinct changes in soil layers.

- Undetectable by Sonic Test: The toe reflection when the Length/Diameter ratio roughly exceeds 20, gradual changes in cross-section, minor inclusions and changes in cross-section, impedance changes of small axial dimension, small variations in length, features located below either a fully-cracked cross section, debris at the toe, deviations from the straight line and from the vertical, the consistency of concrete cover, the length of reinforcement.

Cross-Hole Sonic Testing constraints:

- Detectable: Multiple defects, "soft bottoms" if tubes go to the bottom, voids better than soil inclusions, larger defects easier than small defects, waterfall, FAT (First Arrival Time), and energy all help find defects.

- Undetectable by Cross-Hole Sonic Test: Diameter changes or bulges, if too few tubes, can miss a defect, can find defect on direct path, cannot find defect outside cage, major diagonal defects more difficult to find, need more than 4 tubes for 1500 mm pile (recommend 6 tubes for shaft this size).

4 Conclusions

1. Effective interpretation of PIT test results hinges on both the expertise of the test operator and the meticulous calibration of the instruments.

2. The cost-effectiveness of implementing a quality control program at each construction site far outweighs the potential losses stemming from undetected foundation defects.

3. While the Low Strain test is a cost-effective and efficient quality-control tool, it is essential to recognize its limitations. Despite its quick application time and affordability, it is not infallible. Additionally, the sonic method's efficacy relies on identifying pile attributes that significantly impact wave propagation, typically those of substantial size.

4. Cross-hole logging testing stands out as the most accurate and high-quality method for field observation of deep pile foundations.

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