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Advanced testing methods by SLT and CSL for pile foundations at the Astana Light Rail Transit construction site

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ABSTRACT: This paper presents a comprehensive analysis of the static load testing (SLT) and Crosshole Sonic Logging (CSL) methods used in the construction of the Light Rail Transit (LRT), Kazakhstan. The first phase of the project extends from International Airport to the new railway station, covering a distance of 22.4 km with 18 stations. Bridge foundations are constructed using bored piles with diameters ranging from 1.0 to 1.5 meters and lengths between 8 and 55 meters. To ensure structural integrity and load-bearing capacity, the SLT method, compliant with Kazakhstan's standards and GOST 5686, is employed, requiring that 1% of the piles, with at least two per site, undergo testing. This method measures the axial deformation under incremental loading and unloading, providing essential data through load-settlement curves and strain measurements. Simultaneously, the CSL method, adhering to ASTM D6760-08 (2008) standards, evaluates the homogeneity of pile concrete by transmitting ultrasonic pulses through the concrete and analyzing acoustic parameters like sonic time, frequency, and amplitude attenuation. This method effectively identifies potential defects such as honeycombing, voids, and inclusions. The LRT's pile-raft foundation systems use 4 or 6 piles per support structure, depending on vertical load requirements, with design bearing capacities ranging from 4500 kN to 13000 kN. The concrete used for these foundations is of B40 strength quality, ensuring the durability and resilience necessary for long-term use. The study underscores the critical importance of SLT and CSL tests in guaranteeing the safety and reliability of LRT infrastructure under challenging geotechnical conditions.

KEYWORDS: Pile test, CSL, SLT, LRT.

1 INTRODUCTION

The structural performance of civil engineering structures is essentially determined by the interaction of applied loads, construction quality and material integrity. Deficiencies in any of these aspects can lead to serious consequences such as cracking, uneven settlement or even complete collapse of the structure. Foundations, as the primary load-transfer elements, play a key role in ensuring stability by transmitting forces from the superstructure to substructures with sufficient bearing capacity, while preventing both loss of bearing capacity, characterized by excessive settlement or shear of the soil under load, and structural failure, caused by insufficient material strength or deterioration of the structural integrity. Bored pile foundations are widely used for high-rise buildings, bridges and other large-scale infrastructure projects due to their high bearing capacity and minimal vibration during installation. However, their performance is particularly sensitive to the quality of construction, especially in difficult site conditions where visual inspection during concrete pouring is not possible. Such conditions can result in hidden defects including necking, swelling, cracking, delamination and void formation, which can reduce the load-bearing capacity. To address these risks, non-destructive testing (NDT) techniques have become indispensable for both quality control in new construction and for the assessment of existing structures. Since the 1970s, techniques such as pile integrity testing (PIT) for checking material continuity, continuous borehole sonic logging (CSL) for assessing concrete quality in bored piles and shafts, and continuous borehole tomography (CT) for three-dimensional mapping of defects have become widely adopted, along with parallel seismic (PS), which is particularly valuable for determining foundation depths where direct access to the pile cap is limited. CSL, in particular, has gained prominence for its ability to detect subsurface anomalies by measuring ultrasonic pulse transit time and energy attenuation between access tubes, enabling the precise localization of defects that would otherwise remain invisible. While CSL provides detailed vertical profiling, CT and PIT provide additional information on defect geometry and pile integrity, increasing diagnostic reliability. Despite the effectiveness of these tools, interpretation of results remains sensitive to factors such as concrete age, site-specific conditions and potential interruptions in slab casting. In practice, engineers often encounter situations where only partial information is available on existing foundations; in such cases, determining unknown pile depths or verifying suspected defects is critical to making informed engineering decisions. This study addresses the scenario where the pile type is known but its length remains unknown, using the PS method in combination with CSL, CT and PIT to provide a comprehensive integrity assessment. By comparing field measurements with standardized classification criteria (ASTM D6760-08) and examining practical testing problems, this research aims to improve interpretation procedures, increase the reliability of defect detection, and ultimately enhance safety and cost effectiveness in the construction and maintenance of deep foundations (Buranbayeva, 2022).

The pile testing was carried out using the CHAMP crosshole logging system manufactured by Pile Dynamics Inc., USA. The CHAMP device is designed to measure the "First Arrival Time" (FAT) of the ultrasonic pulse and the signal level (energy). Based on these and other measurements, the propagation velocity of the sound wave through the concrete is calculated, which, together with the signal amplitude, can be used to evaluate the concrete quality. Data recorded by the CHAMP system are subsequently transferred to a personal computer equipped with the CHA-W software, also supplied by Pile Dynamics Inc. This software provides tools for advanced data processing, analysis, and interpretation. Testing is performed using a transmitting and a receiving probe, which are lowered to the same horizontal level in parallel access tubes. Measurements are conducted between all available pairs of tubes. By lowering the probes from the top, the length of the access tubes is determined.

During testing, as the probes are raised simultaneously, measurements are taken at every 50 mm interval. Defects can be identified in locations where the FAT and the signal energy decrease. By transmitting ultrasonic pulses through the concrete from one probe to the other (positioned in parallel tubes), the method assesses the homogeneity of the pile concrete and determines the extent and position of defects, if any. The arrival time of the pulse at the receiving probe and the recorded signal level are directly influenced by the quality of the concrete or the absence thereof. For equidistant access tubes in homogeneous concrete, the FAT and the signal amplitude remain uniform along the pile length. Heterogeneities such as contamination, weak concrete, soil inclusions, voids, or foreign materials cause an increase in FAT and a reduction in signal energy. In cases where a defect is detected, additional testing methods may be applied to the same pile, including Pile Integrity Testing (PIT), static load testing, or coring of the pile concrete at the suspected defect depth. Prior to testing, the pile contractor is required to provide the testing engineer with information on pile length, absolute elevations of the top and bottom of the pile, and the pile casting date. For CHAMP crosshole testing, access tubes must be installed in all piles to be tested. The number of tubes is generally selected at a ratio of one tube per 0.25–0.35 m (10–14 inches) of pile diameter, with at least three tubes in total. The recommended nominal internal diameter of the tubes is 38–50 mm (1.5–2.0 inches). According to TB 10218-2008, the minimum number of tubes is two for piles with diameter $D \leq 0.8$ m, three for diameters between 0.8 m and 2.0 m, and not less than four for $D \geq 2.0$ m. To ensure free and unobstructed movement of the probes inside the tubes, they must be manufactured to standard internal diameters and be free from defects or obstructions, including at tube joints. Adhesive tape or other wrapping materials are not recommended for sealing joints or welds. The contractor should ensure the probes can pass through the full tube length without hindrance. Any joints or damage to the tubes must be documented. After placing the reinforcement cage in the borehole during pile construction, the tubes should be filled with clean fresh water as soon as possible, but no later than one hour after concrete placement. To prevent debris ingress, the tubes should be sealed at the top with caps. Excessive tightening or loading that could damage the tube–concrete interface during cap removal is prohibited. Crosshole sonic testing may be performed at any time after pile installation, though the minimum waiting period is generally two days. TB 10218-2008 specifies that the concrete strength at the time of testing should be at least 70% of the design value and not less than 15 MPa. ASTM D6760 requires a minimum of three days' curing before testing. Since concrete strength and quality increase with curing time, a longer waiting period is generally preferred. Upon completion of crosshole testing and acceptance of the pile by the engineer, water is pumped out from the access tubes, sleeves for cement–sand grout injection are installed to the tube bottoms, and the tubes are subsequently filled with grout (Zhussupbekov, 2019, 2020, 2021).

The final results presented for each tested pile and each pair of access tubes include: (1) a waterfall diagram showing peak signal function versus depth; (2) the calculated FAT versus depth; (3) the calculated relative pulse energy versus depth; and (4) a PDI-TOMO analysis of the pile with representative longitudinal sections and a three-dimensional model showing defects, if present. Defect zones, when detected, are shown on these diagrams and described in the report. Defects are defined as areas where the FAT is increased by more than 20% compared to adjacent zones of sound concrete, combined with reduced pulse energy and lower wave propagation velocity.

Timely and systematic quality control of foundations is a key factor in ensuring both the safety of construction works during the erection phase and the long-term reliability of structures throughout their service life. For pile foundations, particularly bored piles, the early detection of structural defects is of critical importance, as discontinuities in the concrete—such as voids, zones of loosened structure, cracks, or foreign inclusions—can significantly reduce a pile's load-bearing capacity and may lead to the failure of the entire foundation system. Traditional destructive testing methods, which require partial exposure of the structure, are often technically difficult or economically impractical, making non-destructive testing (NDT) methods the primary diagnostic tool for identifying internal defects with high accuracy and without causing damage. These methods are especially valuable for complex, high-responsibility projects where any reduction in operational reliability is unacceptable. Modern construction practice demands that foundation systems combine high specific load-bearing capacity, long-term structural stability over service lives of 50 years or more, resistance to aggressive environmental influences, and verifiability of condition throughout their life cycle. To determine the type and extent of defects in bored piles, specialized data processing software is widely used to generate interpreted pile profiles visualizing structural heterogeneities, compile summary tables of parameters such as wave propagation velocities and reflected signal amplitudes, and perform comparative analysis against regulatory standards. In this study, field tests were carried out using two advanced NDT methods—Pile Integrity Testing (PIT) and Cross-Hole Sonic Logging (CSL). PIT is based on recording the pile's dynamic response to a short impact impulse generated by a specialized hammer, with accelerometers on the pile head detecting vibrations that are analyzed to locate wave reflections, determine the actual pile length, detect cracks or cross-section changes, and assess concrete uniformity; it offers rapid, non-destructive application to all pile types regardless of installation method. CSL, by contrast, relies on ultrasonic signal transmission between vertical access tubes installed in the pile before concreting, with a transmitter–receiver pair moved along the pile height to record travel times and amplitudes; zones with defects exhibit longer travel times and reduced amplitudes, enabling the creation of detailed three-dimensional models of the pile's internal structure and precise localization of defects. Both methods are widely used in the USA, China, and Europe, and are recognized as next-generation technologies for pile foundation assessment. To ensure a reliable assessment of pile integrity, it is essential to apply additional testing methods in specific circumstances. These include cases where the recorded signals are irregular, complex, and unstable, making accurate interpretation and evaluation impossible; situations where the designed pile length differs from the actual pile length without any explanatory notes or supporting documentation; instances in which the pile shaft sections change periodically or noticeably, and where the characteristics of cast-in-place concrete piles vary significantly; and conditions where the reflection from the pile base is weak or indistinct, preventing a confident determination of both the pile's integrity and its actual length. During the evaluation phase of pile integrity testing, each tested pile is classified according to the severity of detected defects. The classification system includes four categories: Type I – piles with an intact shaft; Type II – piles with minor shaft defects; Type III – piles with evident shaft defects; and Type IV – piles with severe shaft defects.

In this paper, they were applied to the Light Rail Transit (LRT) construction sites in Kazakhstan, allowing for a comparative evaluation of their effectiveness and the development of recommendations for adapting them to the conditions of Kazakhstan (Zhussupbekov, 2018, 2020, 2019, 202).

2 NON-DESTRUCTIVE TESTING OF PILES

2.1 *Pile integrity testing (PIT) or sonic integrity testing (SIT) in construction site*

The experimental program was conducted at a light rail transit (LRT) construction site in Kazakhstan, where the substructure for each column rested on groups of four or six bored piles, with diameters ranging from 1.0 m to 1.5 m and embedment depths between 8 m and 55 m. The design specifications required individual piles to sustain ultimate load capacities between 4,500 kN and 13,000 kN, constructed from B35-grade concrete in accordance with project standards. Quality assurance procedures for structural soundness mandated that, in a four-pile arrangement, one element be examined via cross-hole sonic logging and the remaining three evaluated using low-strain integrity methods; for six-pile arrangements, two piles were subjected to cross-hole testing, while the other four underwent low-strain assessments. By analyzing an extensive dataset collected from piles of 1,000 mm and 1,500 mm diameters, with lengths ranging from 10 m to 55 m, along with data from diaphragm walls and other earth-retaining systems, the foundations were comprehensively characterized in terms of their homogeneity, mechanical performance, geometric accuracy, and continuity (Zhussupbekov, 2020).

a)

b)

a – Pile cap supported by four bored piles; b – Pile cap supported by six bored piles

Figure 1 Excavations with four and six bored piles installed depending on the design load.

The Pile Integrity Testing (PIT) method, also known as the low-strain integrity testing method, is a widely recognized non-destructive acoustic technique used to assess the structural condition of piles and detect potential defects along their length. The testing setup typically includes a calibrated impact hammer for generating an impulse; a highly sensitive accelerometer securely attached to the pile head to capture the pile's dynamic response; a connecting element to transfer the signal; a data acquisition device capable of visualizing, recording, and processing high-speed signals; and specialized software for interpreting the recorded waveforms. The accelerometer converts the mechanical vibrations into electrical signals, which are then filtered, amplified, stored, and analyzed. The choice of impact hammer—whether rod-type or handheld, with varying sizes, lengths, masses, and head materials—depends on the pile type, its dimensions, and the specific testing objectives to ensure the required excitation frequency and energy level. In practice, the pile head is first cleaned to ensure good sensor contact. The test involves applying a light blow to the pile head with the hammer, producing a compressive stress wave that travels down the pile shaft. Any structural discontinuities, such as cracks, changes in cross-sectional area, or material heterogeneity, cause partial wave reflections, which are recorded as anomalies in the signal. The reflected waves from the pile toe indicate the pile's actual length, while intermediate reflections help identify the location and severity of defects. The raw acceleration signal can be interpreted directly, but it is often numerically integrated to obtain a velocity signal, which enhances the clarity of reflections and reveals details that may otherwise be missed. This approach is valued for its speed, cost-effectiveness, and ability to test piles in under a minute without causing damage, making it ideal for routine quality control and large-scale foundation verification.

2.2 *Crosshole Sonic Logging (CSL) for Pile Testing*

Crosshole Sonic Logging (CSL) is a non-destructive method used to assess the integrity of deep foundation concrete. This technique measures the propagation velocity and attenuation of ultrasonic waves traveling between access tubes installed within the reinforcement cage. The primary objective is to detect defects such as voids, inclusions, or zones of weak concrete that may form during the bored pile construction process, for example, due to soil contamination in the concrete mix. CSL is considered one of the most effective methods for quality control of bored piles, with procedures regulated by industry standards. The underlying principle is that changes in the structure and physical-mechanical properties of the material alter the velocity of the ultrasonic wave, which is compared against reference signals to determine pile integrity.

In CSL testing, a transmitter sends ultrasonic pulses through water-filled access tubes to a receiver placed in an adjacent tube. The CHAMP crosshole sonic logging device by Pile Dynamics Inc. (USA) was used in the referenced project, along with CHA-W software for data processing and interpretation. During the test, the transmitter and receiver are lowered to the same depth in parallel tubes and then raised together, taking measurements every 50 mm. The recorded parameters include the First Arrival Time (FAT) of the signal and its relative energy, both of which correlate directly with concrete quality. Defects are typically indicated by increased FAT values and decreased signal strength. Testing is conducted between all possible tube pairs to ensure comprehensive coverage of the pile shaft.

Access tubes, with an internal diameter of at least 50 mm, are installed vertically within the reinforcement cage before concreting, and must be free of obstructions or defects to allow smooth probe movement. Tubes should be filled with clean fresh water within one hour after concreting to ensure proper wave transmission. Their top ends must be sealed with caps to prevent debris entry, and excessive force must be avoided when removing these caps to protect the bond between tube and concrete. CSL testing can be performed at any time after pile construction, but industry guidelines recommend a minimum waiting period: two days per TB 10218-2008 (with at least 70% of the design strength and ≥15 MPa concrete strength) or three days per ASTM D6760. Longer curing times are often preferred to ensure more stable results.

Upon completion, water is drained from the tubes and they are grouted with a cement-sand mixture from the bottom up. For each tested pile and each pair of access tubes, the following results are generated: (1) waterfall plots of signal peaks versus depth, (2) calculated FAT profiles along the pile length, (3) relative energy plots versus depth, and (4) three-dimensional reconstructions of the pile using PDI-TOMO software, including cross-sectional views and defect mapping where applicable. This comprehensive reporting provides engineers with a clear assessment of pile uniformity, allowing timely decisions on further testing or remedial measures if defects are detected.

3 RESULTS AND CONCLUSIONS OF PILE TESTS

The testing of each method to obtain three measurement profiles based on the research results and processing of the results using the specialized CHA-W and PDI-TOMO (Figure 3) programs, the results of processing the obtained information are presented in this paper.

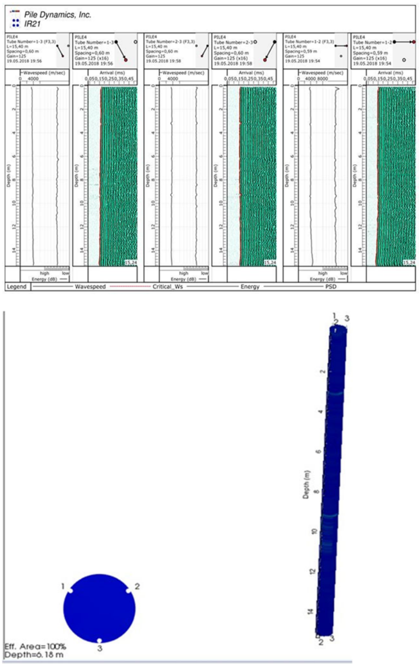

Figure 2 Results of the analyzed tests in the PDI-TOMO program

4 CONCLUSIONS

Allocating resources to a site-specific quality control program represents a small fraction of overall construction costs and is far more economical than addressing failures caused by hidden foundation defects. One of the simplest approaches, the Low Strain test, can be completed in under a minute and offers a budget-friendly option for routine inspections; however, its capabilities are limited. Because this method depends on the travel of stress waves through the pile, it is sensitive only to large-scale irregularities that significantly alter wave transmission. For a more refined analysis, Cross-Hole Sonic Logging (CSL) can be applied, allowing engineers to determine both the location and approximate size of cracks. Although this technique requires the installation of special access tubes during construction, the additional cost is outweighed by its ability to identify problematic areas with much greater precision. Unlike the Low Strain test, which uses relatively long wavelengths—around two meters—the CSL method operates with ultrasonic signals whose wavelengths typically range between 50 and 100 millimeters, offering a much higher level of detail in defect detection.

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