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Wave propagation-based tests for concrete piles – an overview

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Abstract: Non-destructive evaluation techniques for assessing pile foundations have gained significant importance in geotechnical and structural engineering. This study thoroughly assesses the advancements in pile integrity testing from the early days toward current approaches. The study reviews the advancements in pile integrity testing, from early methodologies to modern approaches, while proposing a unique classification of techniques based on their focus: whether they involve the procedure of pile integrity testing or the interpretation of test findings. The analysis declares substantial advancements in testing methodologies, signal processing, and data interpretation techniques for evaluating the structural integrity of deep foundations. The concepts of wave propagation are essential for detecting and evaluating structural flaws, enabling engineers to check pile quality without affecting structural integrity. The review highlights significant issues in pile integrity assessment involving the influence of soil conditions, geometric changes, and material variability on test outcomes. Recent advances have improved the accuracy of flaw detection, enabling real-time monitoring of foundations. Advanced computer techniques now enable more precise test analysis and structural assessments, significantly improving foundation evaluation and safety. This investigation establishes the practical and theoretical basis for implementing advanced machine learning predictive models that combine previous records with pattern recognition algorithms, potentially converting traditional PIT interpretation from an uncertain process to a reliable and precise evaluation system. Conclusions suggest that existing pile integrity testing methods offer thorough solutions for early problem identification and quality assurance in foundation engineering, while also indicating new possibilities for future study and development.

1. Introduction

Concrete structures require non-destructive testing (NDT) to evaluate their performance and condition without causing damage. These tests can assure long-term serviceability, safety,

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and durability of concrete constructions. Early identification of problems, including cracks, voids, or corrosion, is essential to prevent later deterioration and expensive repairs. NDT provides quality assurance during construction, facilitates efficient maintenance planning, and enhances the durability of structures by detecting potential risks before they develop. NDT improves the durability and accessibility of infrastructure by facilitating cost-effective monitoring and enhancing safety measures. NDT techniques, particularly vibration and ultrasonic testing, were examined to track the essential structural integrity of pre-stress loss in concrete bridge structures [1]. Hidden defects, such as cracks, voids, or segregation, can compromise the strength and durability of concrete piles, potentially damaging them. These flaws can be identified early without causing damage to the piles by applying non-destructive testing techniques, such as ultrasonic pulse velocity testing, cross-hole sonic logging, and low-strain integrity testing. This ensures appropriate construction quality, confirms the efficacy of installation methods, and helps identify uncertainties before they lead to structural collapses. The integrity of concrete piles is primarily maintained by NDT, which improves safety, ensures durability, and reduces the need for frequent inspections or expensive repairs [2]. Periodic monitoring of these structures using wave-based NDT enables enterprises to make informed maintenance decisions and improve overall operational safety. Ultrasonic testing utilizes high-frequency sound waves to evaluate the material's internal composition. The pulse-echo technique allows precise identification of defects by analyzing the echo. Through-transmission detects defects by transmitting waves from one side of the material and detecting them on the opposing side. Acoustic emission testing focuses on high-frequency vibrations generated by sudden structural changes, such as crack development, allowing real-time defect monitoring for ongoing assessments of critical structures. Wave propagation techniques enhance safety and durability in structures by detecting faults early, reducing operational costs, and ensuring structural integrity across various engineering fields, as shown in Figure 1.

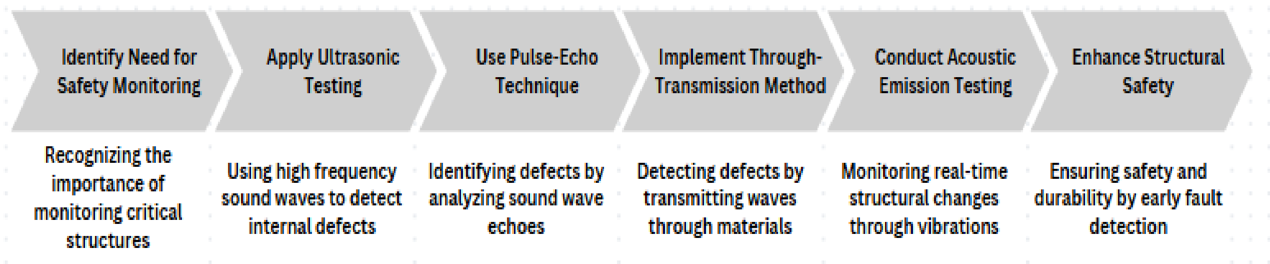


Fig. 1: Wave Propagation Techniques in Structural Safety

2. Methodology

The methods for collecting research are divided into different wave-based non-destructive testing methods: Ultrasonic Pulse Velocity (UPV), Pile Integrity Test (PIT), Cross-hole Sonic Logging (CSL), Statnamic Rapid Load Test (RPLT), and Dynamic Pile Load Test (DPLT). The technical analysis framework assesses each method based on performance criteria. Eight approaches examine advanced interpretation techniques simultaneously. The methodology revealed findings through a gap analysis that identified critical research needs.

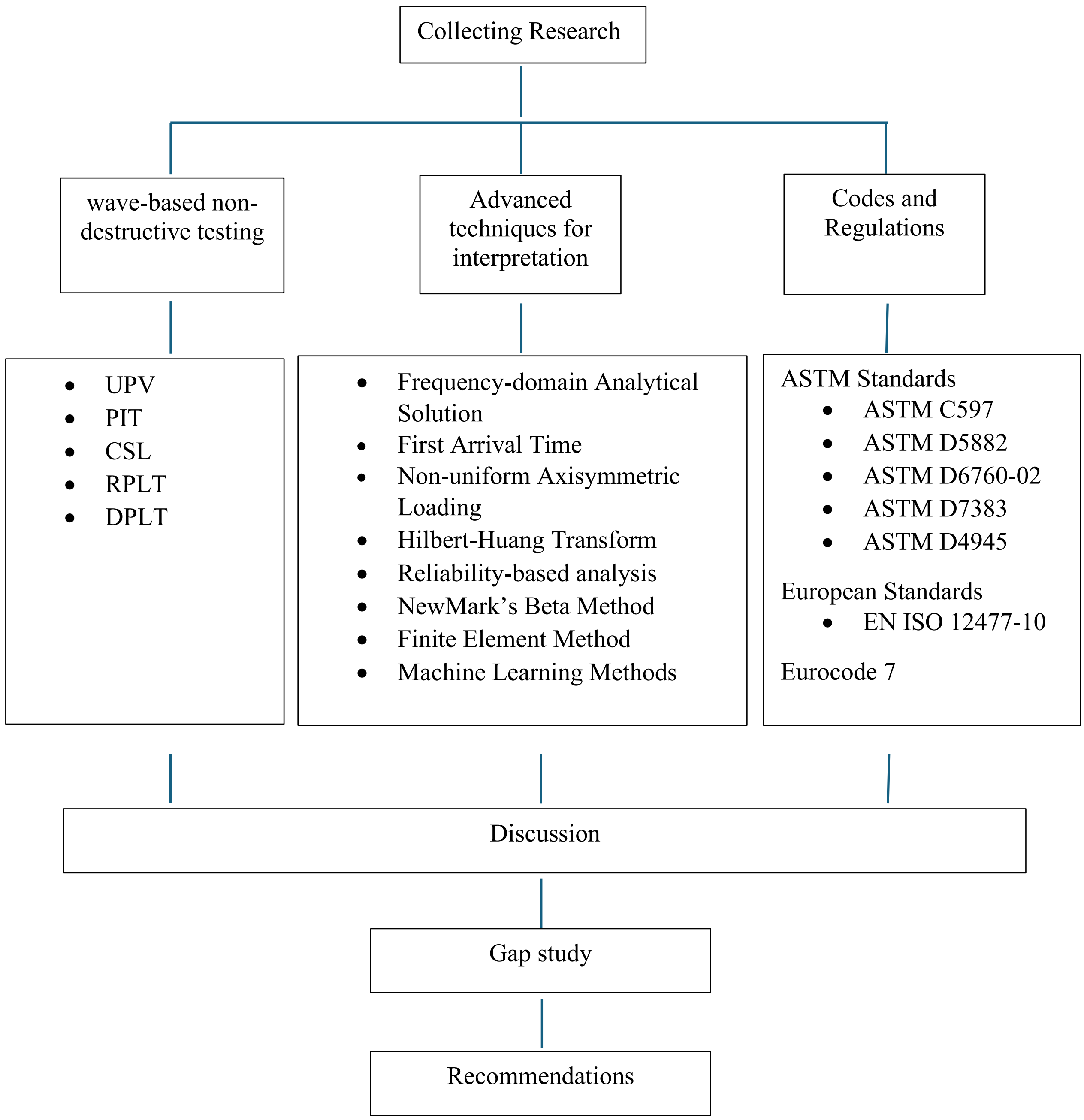


Fig. 2: Methodology flowchart for wave propagation-based non-destructive testing methods for concrete piles

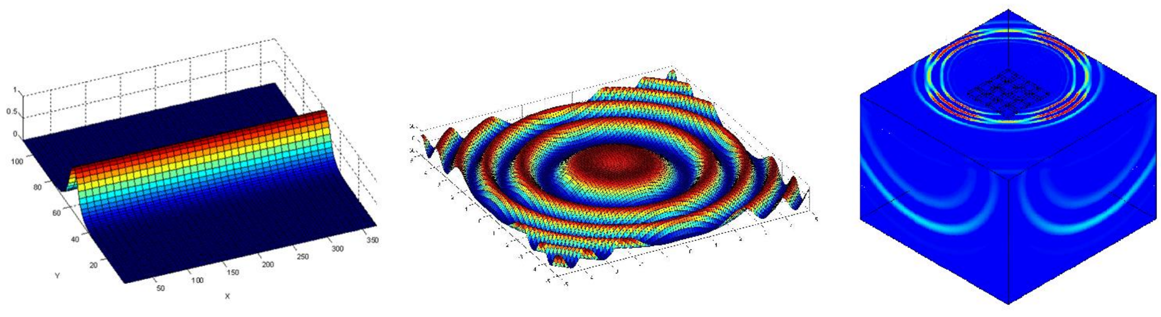
3. Background about wave propagation in solids

Wave propagation is a fundamental concept in civil engineering, playing a pivotal role in assessing the health of structures by detecting cracks, flaws, or irregularities. In media where properties remain consistent, such as homogeneous materials, wave behavior tends to be predictable and follows straightforward patterns. However, in non-homogeneous media, varying densities, elasticities, or stiffnesses cause such as reflection, refraction, scattering, and mode conversion. These complexities make it challenging to predict wave propagation in real-world structures. The general form of the wave equation in three dimensions is presented in Eq. 1, where u(x,y,z,t) is the displacement of the wave at position (x,y,z) and time t, v is the speed of the wave in the medium, $\partial^2 u/\partial t^2$ The second derivative of u with respect to time, representing the acceleration of the wave, and $\partial^2 u/\partial x^2$, $\partial^2 u/\partial y^2$, $\partial^2 u/\partial z^2$ The second derivative of u, with respect to the spatial coordinates x, y, and z, represents the wave's curvature in each direction [3].

$$\text{Equation 1: } \frac{\partial^2 \boldsymbol{u}(x,y,z,t)}{\partial t^2} = v^2 \left(\frac{\partial^2 \boldsymbol{u}(x,y,z,t)}{\partial x^2} + \frac{\partial^2 \boldsymbol{u}(x,y,z,t)}{\partial y^2} + \frac{\partial^2 \boldsymbol{u}(x,y,z,t)}{\partial z^2} \right) \quad [3]$$

In a one-dimensional spatial context, the most straightforward wave is a sine wave with a varying amplitude, A, described by the equation A(x, t) = A0 sin(Kx - ωt), where A0 is the maximum amplitude. Here, K, known as the wave number, is given by K = 2 π/λ, where λ is the wavelength, and ω, the angular frequency, are expressed as ω = 2πf, where f is the wave frequency. Waves that propagate horizontally in two dimensions, with surface displacement, can be described by a similar function: $A(x,y,t) = A_0 \sin(Kx - \omega_x t + Ky - \omega_y t)$. Extending this to three dimensions, the sinusoidal representation of a mechanical wave becomes $A(x,y,z,t) = A_0 \sin(Kx + Ky + Kz - \omega t)$, accounting for the wave's behavior in all three spatial directions over time. The non-homogeneous wave equation in three dimensions (3D) is expressed in Eq. 2. This equation accounts for variations in wave speed caused by changes in material properties across the medium. The term f(x,y,z,t) represents an effective disturbance factor that models the impact of irregularities within the medium. These irregularities can arise from variations in material properties, allowing the wave equation to describe behavior in non-uniform materials. Such changes create internal "sources" of disturbance, which disrupt the wave's propagation and influence its behavior.

$$\text{Equation 2: } \frac{\partial^2 \boldsymbol{u}(x,y,z,t)}{\partial t^2} = v^2 \left(\frac{\partial^2 \boldsymbol{u}(x,y,z,t)}{\partial x^2} + \frac{\partial^2 \boldsymbol{u}(x,y,z,t)}{\partial y^2} + \frac{\partial^2 \boldsymbol{u}(x,y,z,t)}{\partial z^2} \right) + f(x,y,z,t) \quad [3]$$



1D **2D** **3D**

Fig. 3: Wave propagation in 1D, 2D & 3D [4] **.**

The wave velocity v in a material is determined by its mechanical properties and is given by Eq. 3 as follows:

$$\text{Equation 3: } v = \sqrt{\frac{E\,(1-\mu)}{\rho\,(1+\mu)(1-2\mu)}} \qquad [3]$$

This equation relates the wave velocity to the dynamic elastic modulus (E), density (ρ), and dynamic Poisson's ratio (ν), providing a measure of how waves propagate through materials such as concrete, where typical velocities range from 3500 to 4000 m/s.

4. Wave propagation-based non-destructive tests for concrete piles in solids

4.1. (UPV) test

A range of essential procedures is involved in the UPV testing process to ensure an accurate evaluation of the material's qualities. First, the test material's surface is cleaned to eliminate dust, debris, or loose particles that could interfere with ultrasonic wave transmission. The surface may be smoothed to enhance contact between the transducers and the material. After that, the UPV apparatus, which includes a transmitter, receiver, and coupling gel, is assembled, as shown in Figure 4. The coupling gel is placed in the contact points to improve the transmission of ultrasonic pulses into the material. Three primary arrangements are possible for the transducers: indirect transmission (on the same surface, appropriate for surface inspections), semi-direct transmission (on nearby surfaces), and direct transmission (on different sides of the material for the highest energy transfer). Once in place, the transmitter sends a pulse that passes through the material and is taken by the receiver. The UPV device records the pulse's travel time. International standards, such as ASTM C597 (Standard Test Method for Pulse Velocity through Concrete), can serve as guidelines for UPV testing parameters [5]. The transducer frequency typically ranges from 20 to 100 kHz, with operating temperatures between 0 and 40°C. Saturated concrete can have a pulse velocity that is up to 5% greater than that of dry concrete. A coupling agent, such as petroleum jelly or grease, is put between the transducers and the test material to ensure adequate energy transfer and remove air gaps. A reference bar with a known transit time is used for calibration. UPV offers high-resolution detection, enhanced depth estimation, and improved differentiation of structural irregularities. The limited depth and sensitivity to surface conditions can restrict the practical evaluation of soil stiffness, requiring careful consideration of pile composition for accurate analysis. Li, in structural health monitoring, explores the use of guided ultrasonic waves to identify part-thickness cracks. It uses the symmetric (S0) mode and its transition into anti-symmetric (A0) and shear horizontal (SH0) modes after fundamental Lamb waves interact with material defects. The examination analyses defect depth, length wave scattering, and conversion phenomena using finite element (FE) modeling and experimental validation. The mode-converted A0 mode amplitude increases with defect length, culminating at three-quarters of defect depth. SH0 is sensitive to shorter faults. Guided wave mode conversion can detect early cracks in thin-plate structures with improved sensitivity and accuracy for structural health monitoring [6].

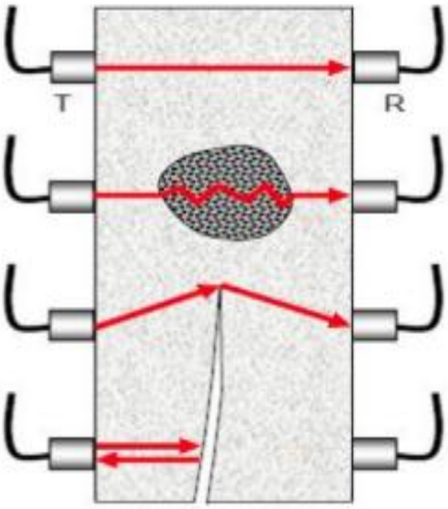


Fig. 4: The concept of the UPV test [7] **.**

4.2. (PIT)

To assess the structural integrity of piles and detect possible flaws, such as cracks, holes, or changes in material properties, the pile integrity test utilizes stress waves generated by light impacts. To ensure precise outcomes, the process starts with surface preparation, which involves cleaning and smoothing the pile head. After attaching an accelerometer to the pile head, a hand-held hammer is used to strike the pile, creating a stress wave that travels the length of the pile. The sensor records the time and amplitude of the reflections when this wave reflects from the pile toe or any other flaw in the pile. Significant waveform shifts may indicate structural problems in the velocity or acceleration versus time graph, which displays the collected data, as shown in Figure 5. A signal's smooth decline indicates a sound pile, whereas early reflections suggest faults. Following the test, a thorough report is provided, including suggestions, a summary of the equipment and methodology, graphical findings, and any anomalies identified. Accelerometer signals, which should be positioned close to the pile head and have a sensitive axis parallel to the pile axis, can be integrated to provide velocity data. Accelerometers with a resonance frequency of at least 30,000 Hz and a time constant 0.5 seconds can be utilized for A/C or D/C applications, with a duration of more than 0.5 seconds. Transducers that measure displacement or velocity can also be employed. The motion sensor should be positioned close to the pile measurement of axial pile motion. More places should be considered for piles that are more extensive than 500 mm. Low-strain impact should be applied if the sensor is 300 mm away; if inaccessible, it must be attached to the pile shaft. The motion sensor should be positioned close to the pile measurement of axial pile motion. More places should be considered for significant piles exceeding 500 mm in height. Low-strain impact should be applied if the sensor is 300 mm away; if inaccessible, it must be attached to the pile shaft [8]. PIT can detect common defects, including necking, bulging, fractures, and voids. Although it is a quick, cost-effective, and nondestructive test that works well for various pile types, wave attenuation and its limited ability to identify minor flaws may restrict its applicability for very long piles [9]. Surya J. Varma's study illustrates data analysis in both time and frequency domains, utilizing pulse-echo and transient response techniques, facilitating defect identification and pile length assessment. PIT proved effective in confirming pile length and detecting material non-homogeneity at depths. The value of outcomes depends on resolution, signal interpretation, and testing settings. A distinct wave reflection pattern is crucial for precise interpretation. Impedance (Z): Indicates resistance within the pile, aiding in the evaluation of material quality and cross-sectional area. Variations in impedance suggest possible structural defects [10]. Mahesh Hingorani explains how to analyze and interpret pile integrity test results from many project sites using the Pulse Echo Method and various construction techniques in Indian soil conditions. PIT can test piles with an L/D ratio of 30 or less but doesn't generate data on pile capacity or load transfer mechanics. It can detect flaws and length, but it's influenced by assumptions during signal processing. PIT results can fluctuate by up to 10%, especially when wave speed fluctuations are plausible due to pile material quality. ASTM D 5882 categorizes test results into four groups in Figure 6: A - Distinct toe reaction with no noticeable flaws; B - Clear indication of a significant defect; C - Indication of a possibly defective shaft; D - inconclusive information. • Category A piles exhibit consistent uniformity within the methodology's accuracy parameters. • Category B piles are substandard and questionable, requiring a contingency plan. • Category C piles may be allocated a diminished capacity and undergo additional tests or excavation. • Category D piles may exhibit substandard data due to inadequate concrete quality at the pile apex. Reducing the pile to a lower height and retesting the pile is an option. Elongated or uneven pile geometries can also contribute to inconclusive data [11][12]. Shi-Wei Hou utilized ABAQUS/Explicit to simulate low-strain testing of defective piles, thereby providing reliable results. Analysis of the effects of cross-sectional area, defect thickness, and material properties on wave reflection patterns led to the identification and localization of various pile flaws, such as necking, spreading, and segregation [13].

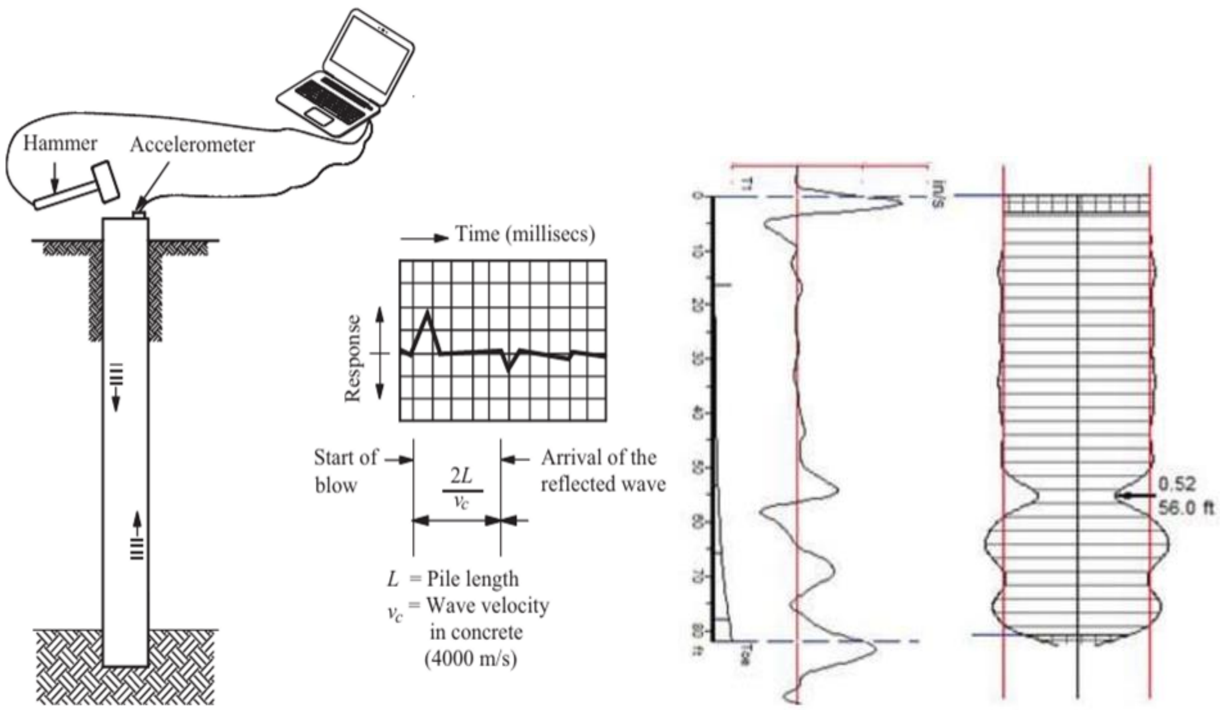


Fig. 5: The setup and results of the pile integrity test [14] **.**

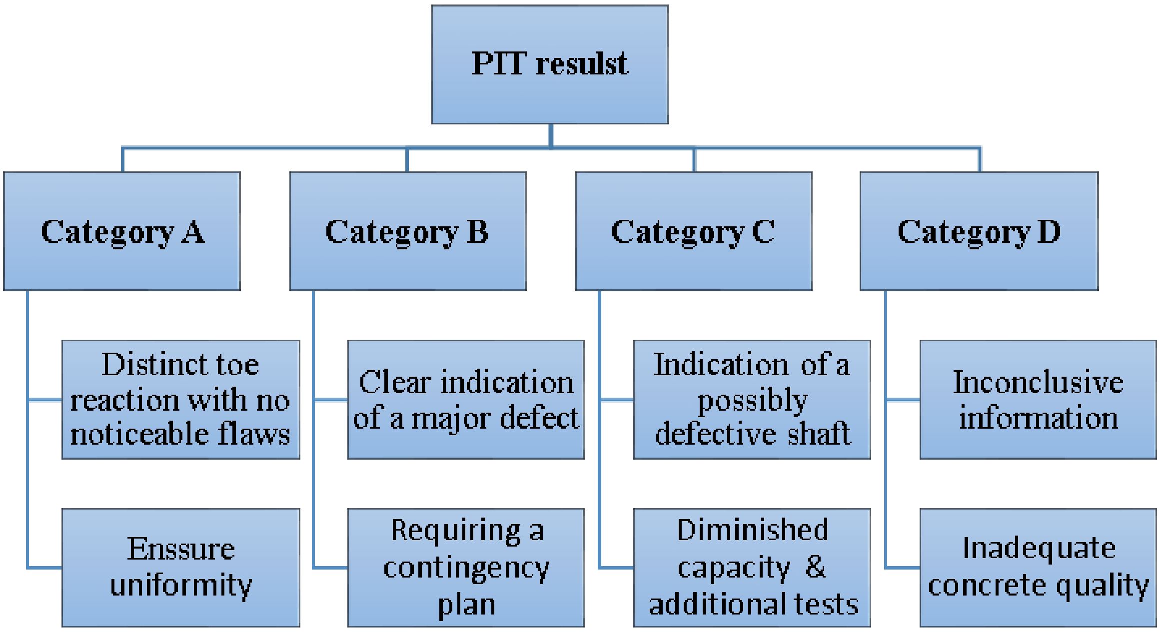


Fig. 6: Categorization of Test Results According to ASTM 5882 [12] **.**

4.3. (CSL) test

CSL is a nondestructive testing technique used to evaluate the integrity of drilled or cast-in-place concrete foundations. Vertical steel or PVC access tubes should be installed to facilitate the pouring of concrete. Three to four tubes are typically employed, positioned uniformly apart, and fastened to the reinforcing cage, as shown in Figure 7. The tubes are well-sealed at both ends and are watertight. The access tubes should be undamaged and in one piece while pouring concrete. To ensure steady transmission of ultrasonic waves, the concrete must be given enough time to cure. The steady transmission of ultrasonic waves requires that the concrete be given sufficient time to cure for at least seven days. To enhance the acoustic interaction between the transducers and the concrete, the access tubes were filled with clean water before testing. Tomographic images, amplitude values, and velocity-time graphs should all be included in the data. According to ASTM D 6760, the internal diameter of access ducts is typically between 38 and 50 mm. The ultrasonic pulse produced by the transmitter probe must have a minimum frequency of 30,000 Hz. Each probe must have centralizers with an effective diameter equal to at least 50% of the access duct diameter if the transmitter, receiver, or both are smaller than half of that diameter. The receiver probe's data-collecting process will begin instantly with each ultrasonic pulse delivered. An analog-to-digital converter with a minimum amplitude resolution of 12 bits and a minimum sampling frequency of 250,000 Hz must digitize the analog signals of an ultrasonic pulse measured by the receiving probe [15]. CSL is suitable for locating voids, defects, or flaws in reinforced concrete piles due to its high accuracy. This accuracy facilitates informed decision-making in construction and quality control, enabling accurate assessments of foundation integrity. CSL is ineffective for piles not adequately prepared before testing, necessitates pre-installed tubes, and is cost ineffective. Reliability is measured using inspection probability, which integrates the encountered probability (the possibility of a defect existing within the testing area) and the detection probability (the ability to recognize the flaw when it is present). Mathematical models are formulated to compute the encountered probability, whereas detection probability is obtained from existing CSL test data. The analysis indicates that CSL's minimum detectable defect size decreases with an increase in pile diameter, provided number of access tubes remains constant. The necessary quantity of access tubes for practical applications can be estimated according to the intended encounter probability. For example, obtaining a 95% detection probability necessitates three access tubes for identifying faults above 15% and four tubes for problems reaching 5% of the pile's cross-sectional area. This approach enhances both the theoretical understanding and practical application of CSL testing, improving the theoretical comprehension and practical implementation [16] [17].

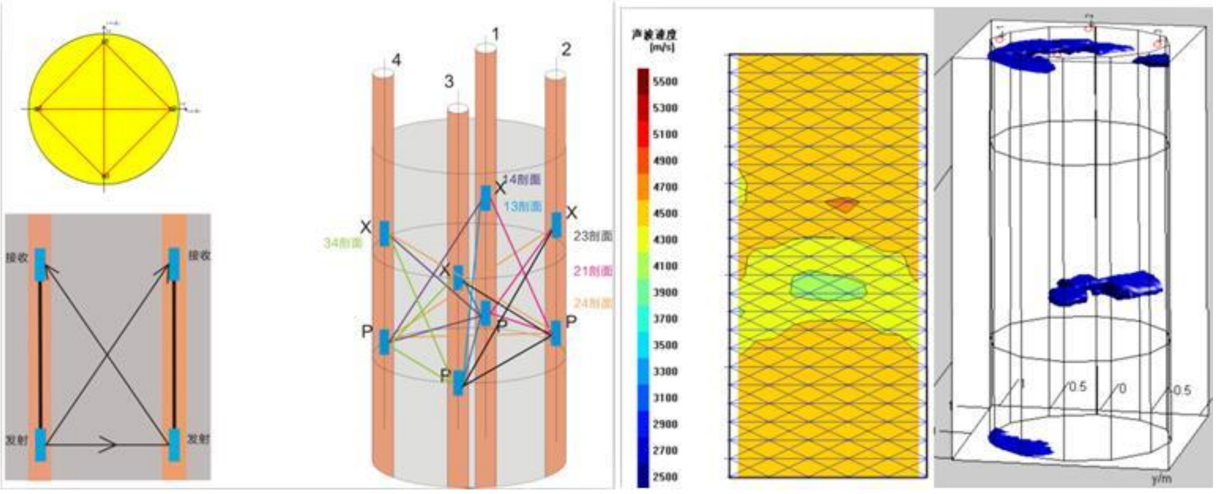


Fig. 7: Cross-hole test setup & results [15] **.**

4.4. (RPLT)

A specialized technique called RPLT simulates static conditions by providing a load that increases quickly to assess the deep foundation's ability to support loads. As shown in Figure 8, the RPLT setup comprises key components, including the gravel container, gravel, masses, combustion chamber, and pile. First, the pile or foundation element is installed following the design specifications. Next, the Statnamic device is set up on the pile head. This apparatus consists of sensors for data collection, a combustion chamber or gas pressure system for producing the load, and a heavy reaction mass. Fuel is ignited, or compressed gas is released to make a controlled reaction force that pushes the pile downward for 100–200 milliseconds. Static load capacity and load-displacement behavior are determined by recording and analyzing acceleration, load, and displacement data using mathematical models. With a typical load range of 100 to 30,000 kN, the test is suitable for driven piles, bored piles, and other types of deep foundations. The setup follows ASTM D7383 and utilizes a reaction mass suitable for the test load [18]. It takes much less time than conventional static load testing to provide a near-static load simulation. Also, fewer complex reaction systems are needed than for static tests. This test can effectively test piles with a large capacity and is appropriate for urban settings because it produces minimal vibration. However, it requires specialized knowledge and complex equipment. Complex mathematical modeling is used in the investigation to isolate dynamic impacts. Also, it could be costly for small enterprises and restrict dependability in particular soil types. Nguyen Quang Huy investigated RPLT as a more straightforward analysis approach than dynamic load testing and a less time-consuming alternative to static load testing. Numerical simulations, 1g and centrifuge model testing, and laboratory triaxial tests were combined to resolve the uncertainties related to rate effects and excess pore pressure in the sand [19]. Poh Hai Ooi and Yong Ping Oh evaluated the effectiveness of RPLT as an alternative to traditional static pile load testing for bored piles. It is shown that the load-displacement behavior of RLT was almost the same as static testing at comparable static loads for pile settlements smaller than 3% of the pile diameter. A site-specific correction factor, verified through calibration testing by EN ISO 12477-10, is recommended for settlements exceeding 3%. These findings provide reliability to RLT as a dependable and effective substitute for conventional static load testing techniques in pile design for a range of ground conditions [20].

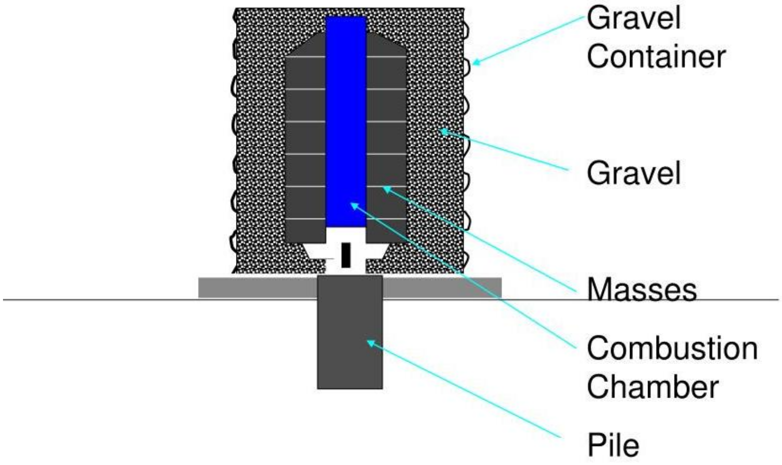


Fig. 8: Statnamic (Rapid) pile load test setup [18] **.**

4.5. (DPLT)

DPLT is a commonly used technique for assessing the capacity of piles and their load-displacement behavior. A drop hammer or comparable tool is required to apply a high-strain impact force on the pile head, while accelerometers and strain gauges track. At the same time, accelerometers and strain gauges require a comparable tool to apply a high-strain impact force to the pile head. In contrast, accelerometers and strain gauges track the force and velocity. The test results are analyzed using wave equation analysis or signal-matching techniques to assess the pile's dynamic properties and static bearing capacity. It features a driving hammer or dropped mass that applies impact forces to the pile through a striker plate, cushion, accelerometers, and strain gauges, located on either side of the pile, that detect velocity and force, as illustrated in Figure 9. An acquisition system receives data for analysis, and a theodolite records pile movement or displacement. Concern for codes such as ASTM D4945, high sampling rate to obtain impact data quickly (usually 10 kHz or more). A minimum sampling rate of 10,000 samples per second is frequently necessary for dynamic signals. The accelerometers must be inserted in the pile and mounted on the pile using tiny, stiff metal blocks that are solid, almost cubic, or directly connected to the pile surface. Transducers should be placed at least 1.5 times the pile width from the top (or bottom) to prevent asymmetrical stress concentrations at the pile's ends [21]. DPLT is significantly more cost-effective and time-efficient than static load tests [22]. The test can be completed rapidly and doesn't require many setups, making it ideal for large-scale projects with several piles; however, it is challenging because dynamic effects are involved. Furthermore, the method requires careful calibration and validation against the findings of static load tests in some situations due to its high sensitivity to soil type, pile material, and impact energy. Elmesallmay identified damage in the shallow foundation utilizing PIT to locate cracks in reinforced concrete footings. The dynamic load used is an impact load. Correction methods were developed to analyze PIT signals and graphs to detect damage. The propagation of stress waves in piles is simulated using ADINA software, classifying wave behavior according to properties [23]. The Pile Dynamic Analyzer (PDA) test provides a cost-efficient and rapid alternative to traditional load testing, evaluating pile integrity without requiring heavy onsite equipment [24].

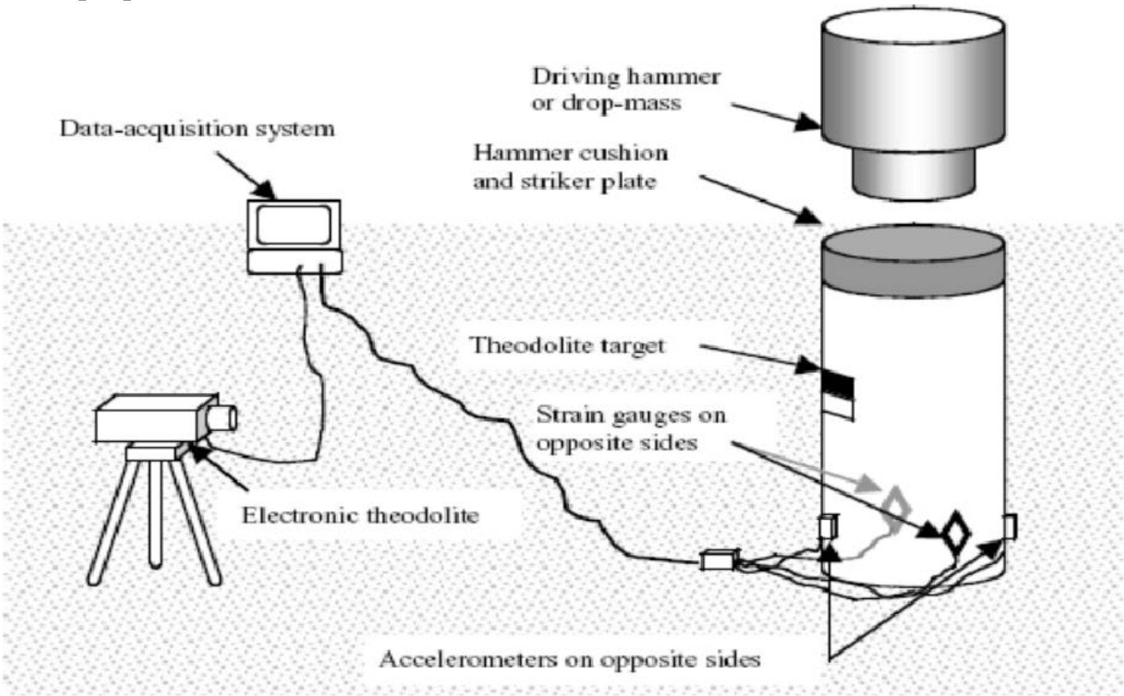


Fig. 9: The setup of dynamic pile load test [25] **.**

5. Advanced techniques for interpretation of wave propagation-based NDT results

5.1. Frequency-domain Analytical Solution

First, the signal can be visualized in the time domain, where the amplitude is plotted against time. A sequence of sinusoidal components, or sine and cosine waves, each with a specific frequency, amplitude, and phase, forms the signal, as shown in Figure 10. The signal appears as a sequence of vertical lines (or spikes) in the frequency domain, each representing the frequency of a sinusoidal component. The height of each line indicates the sinusoid's amplitude at a given frequency. In the frequency domain, frequencies that lack a corresponding sinusoidal component are absent. Fourier Transforms (or their computational cousin, the Fast Fourier Transform, FFT) are commonly used to convert data from the time domain to the frequency domain. Dominant and minor frequency components are revealed by converting the continuous waveform into its frequency spectrum using mathematics. Frequency-domain analysis is employed in dynamic pile load testing to examine how stress waves propagate through the pile, assess the impact of soil-pile interaction on wave patterns, and utilize frequency content analysis to identify anomalies in the pile, such as flaws or discontinuities [26]. Ding et al. explored three-dimensional wave propagation in large-diameter pipe piles during low-strain integrity assessments, utilizing the Winkler model to address flaws such as varying wall thickness and Young's modulus. The model's predictions of velocity and displacement responses can help identify faults via reflected forms. The properties of materials, pile geometry, and stimulation parameters have a significant influence on wave behavior. Defect influence reflected waves, enabling the identification of defect types and severity. Methodologies are presented to determine depth and classify defects, thereby improving the reliability of pile integrity assessment. Structural defect analysis is essential for maintaining the integrity and safety of several structures. Numerous methodologies have been established to detect, evaluate, and interpret structural faults [27].

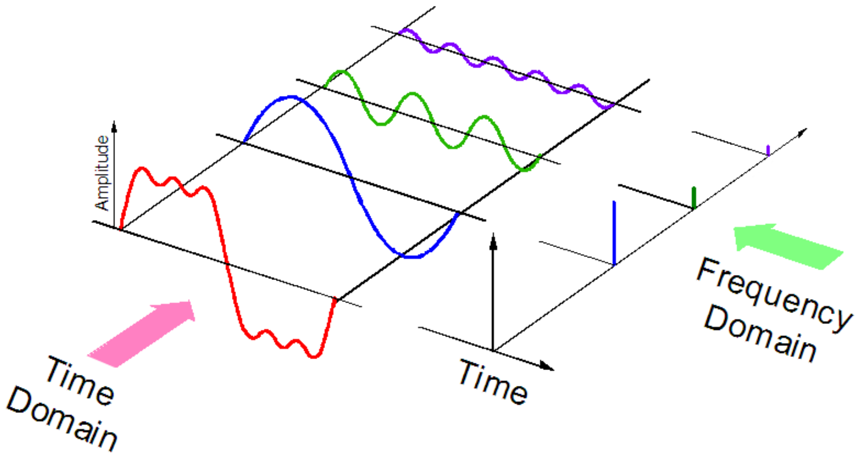


Fig. 10: The concept of frequency-domain analysis [28] **.**

5.2. First Arrival Time (FAT)

FAT approach is used in geotechnical and structural analysis to identify the first wave that reaches a sensor or measuring point. A vertical dashed line on the graph, as shown in Figure 11, indicates FAT, which shows a signal plotted as amplitude vs. time. After this, the signal shifts, reflecting any further wave behavior or reflections. This method is crucial for assessing pile length, material characteristics, and anomalies. Webster et al. focus on interpretation, which entails evaluating Signal Energy and FAT, utilizing a suggested classification scale (Good, Questionable, Poor/Flaw, Poor/Defect). The requirement for additional mitigation measures (e.g., tomography, load testing) depends on the severity and scope of the defects. Low-strain testing is efficient for piles that lack pre-installed inspection tubes and is especially advantageous for smaller-diameter piles. Reflections from the top to the bottom of the pile assist in identifying defects in material quality or shaft dimensions [29].

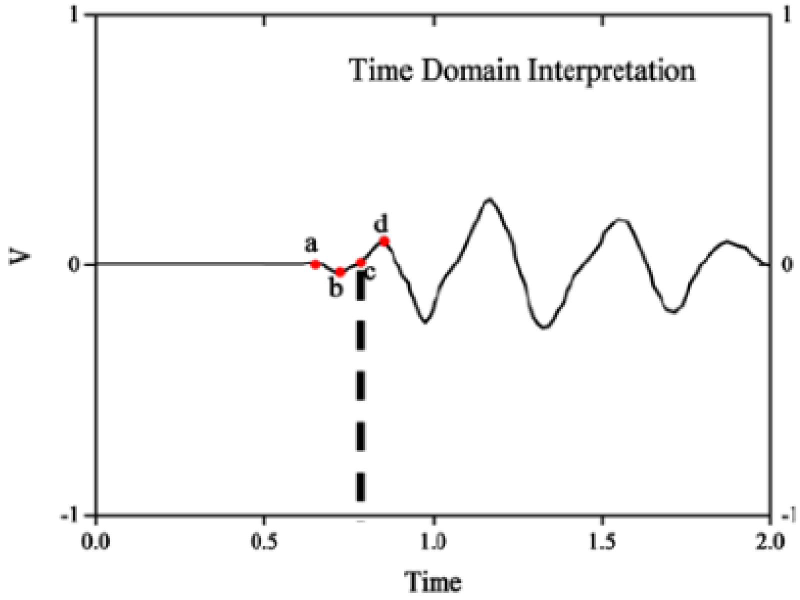


Fig. 11: Determination of First Arrival Time [30] **.**

5.3. Non-uniform Axisymmetric Loading (NAL)

In PIT, non-uniform axisymmetric loading refers to applying a load that varies across the pile's cross-sectional area while maintaining symmetry around its axis, as shown in Figure 12. By creating stress waves that travel through the pile and enabling the detection of flaws such as cracks, holes, or changes in material properties, this technique assesses the structural integrity of piles. This method enhances the test's sensitivity by simulating real-world stress situations, thereby exposing flaws that uniform loading would otherwise miss. A thorough evaluation of the pile's quality and performance is provided by symmetric loading, which ensures consistent data interpretation. It is beneficial for spotting minor deficiencies and ensuring pile reliability under challenging stress conditions. Xin Liu's Non-Uniform Axisymmetric Loading model in (PIT) addresses the limitations of traditional rod models by considering both radial and vertical forces. Parametric analyses optimize factors like loading area, excitation duration, and test point locations, improving test result reliability and assessing pile performance and structural integrity [31].

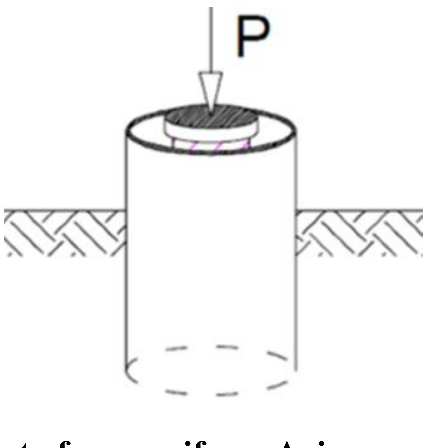


Fig. 12: The concept of non-uniform Axisymmetric Loading [32] **.**

5.4. Hilbert-Huang Transform (HHT)

The HHT is a technique for analyzing data designed for nonlinear and nonstationary signals. It offers a more precise approach compared to conventional methods, such as the Fourier or Wavelet transforms. Intrinsic Mode Functions (IMFs) and a residual trend are generated as the technique decomposes a complex signal into several smaller components. The procedure illustrated in Figure 13 is described as follows: The top panel displays the original input signal, which is non-linear and non-stationary. It contains multiple oscillatory components, with IMF 1 being the highest-frequency component. IMF 2 captures slower oscillations, while IMF 3 captures broader ones. Each IMF is designed to reflect a single mode of oscillation. The residual panel displays the non-oscillatory trend that remains after extraction. Jiang et al. propose a unique technique for evaluating pile integrity that employs low-strain reflection testing in conjunction with the HHT and a multi-channel annular array configuration. An eight-channel PZT transducer array captures defect-related reflections in model heaps, facilitating accurate 3D imaging of defect kinds and locations. The HHT signal processing application, primarily utilizing Empirical Mode Decomposition (EMD), effectively distinguishes defect signals from ambient noise, thereby enhancing precision in identifying and localizing damage within piles. An experimental platform substantiates this strategy, illustrating that the technology exceeds conventional low-strain testing instruments in defect identification precision. This innovation offers a dependable and comprehensive visualization of pile integrity, improving diagnostics for structural safety [33].

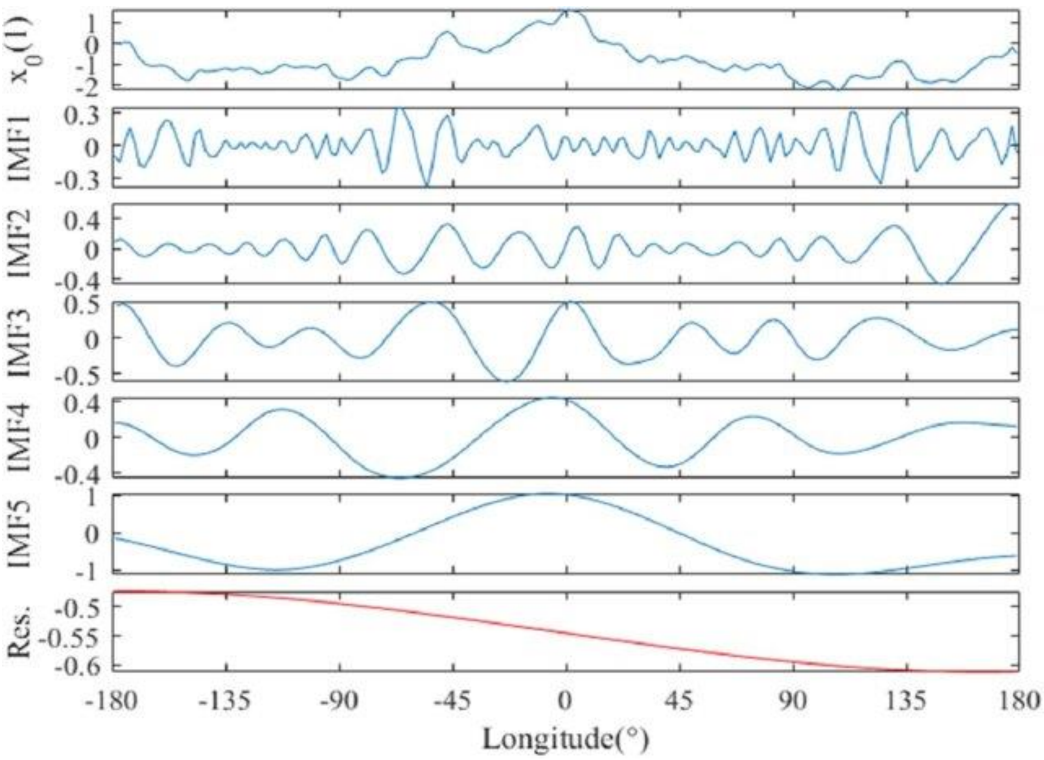


Fig. 13: The concept of Hilbert-Huang Transform [34] **.**

5.5. Reliability-based analysis

Reliability-based analysis is a probabilistic method that considers variations in parameters such as load (S) and resistance (R) to evaluate the performance of systems under uncertainty.

This method uses statistical techniques to determine the probability of failure when the load exceeds the resistance (R < S). Marginal distributions illustrate the individual variability of each parameter in the analysis of the combined probability density function (PDF) of R and S, as shown in Figure 14. The safe domain (R>S) and the failure domain (R<S) are separated by the boundary R=S. The probability of failure is calculated by integrating the joint PDF over the failure domain, providing a graphical representation of reliability. According to Teixeira et al., reliability-based analysis ensures safer designs for pile foundations by optimizing pile dimensions to meet target reliability indices by codes such as Eurocode 7. Compared to conventional deterministic safety factors, this probabilistic method enhances design transparency and precision, particularly in situations involving complex uncertainties. This method calculates the reliability index (β) and probability of failure (Pf) by assessing uncertainties from multiple sources, including soil variability, modeling mistakes, and load characteristics. The study defines a performance function (M=R−S) to compare resistance (R) and load (S). It divides uncertainties into geographic variability, transformation errors, and statistical estimation mistakes using techniques such as Monte Carlo Simulations (MCS) [35].

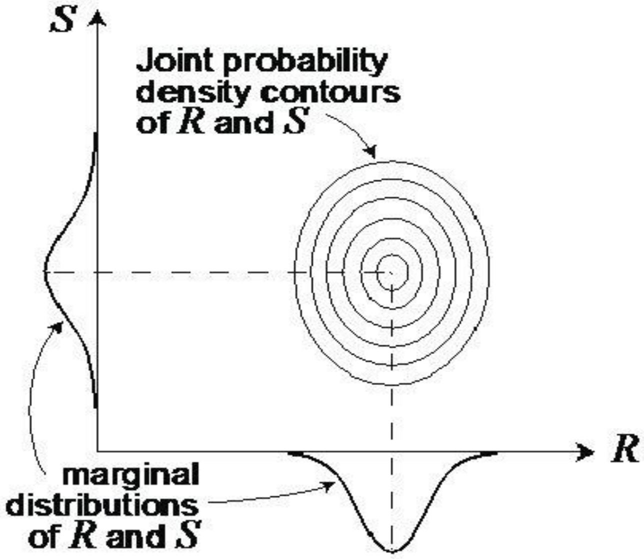


Fig. 14: The concept of Reliability-based analysis [36] **.**

5.6. NewMark's Beta Method

Newmark's Beta Method is frequently used to analyze seismic reactions, vibrations, and dynamic interactions in structures because of its adaptability and efficiency in managing linear and non-linear systems. Under dynamic loads, such as earthquakes, it computes time-dependent reactions, including accelerations, velocities, and displacements. To control numerical damping, stability, and accuracy, the approach discretizes time and uses parameters β and γ to approximate solutions. The applied forces and system characteristics like mass, stiffness, and damping are used to calculate displacements and velocities at each time step. Likins and Rausche evaluate potential damage by analyzing stress wave reflections, with a focus on critical areas, such as pile splices near the toe. Dynamic monitoring and the Beta Method (ß-Method) are reliable for assessing pile damage during installation, particularly for high-stress piles. Real-time data from strain and acceleration sensors, combined with CAPWAP signal matching, ensures pile acceptance or rejection [37].

5.7. Finite Element Method (FEM)

The Finite Element Method is used to analyze the integrity of piling foundations. Three subfigures that highlight various aspects of the FEM model utilized in pile integrity testing are illustrated in Figure 15: (a): The soil mass, the pile, and the reinforced concrete cage (RFT cage) are the main elements of the FEM model. The FEM simulation, which enables in-depth stress and strain analysis in the pile and surrounding soil, requires that each component be represented in a discretized grid format. (b) This subfigure illustrates the geometric configuration and boundary conditions of the FEM model, which includes a pile embedded within a soil mass of a specified dimension. Boundary constraints ensure that specific displacements and rotations (U3=UR1=UR2=0) are limited to reflect realistic soil-pile interactions. A symmetrical surface is defined along the Z-axis to simplify the computational domain and reduce the model size without reducing accuracy. (c) The subfigure demonstrates the interaction between a pile and its surrounding soil. It focuses on frictionless contact along the pile's lateral surface and frictional interactions at interfaces, such as the integrated reinforced cage. Chow et al. highlighted the limitations of traditional 1D stress wave theory by using the FEM to investigate the 3D impacts in low-strain pile integrity testing. Considering boundary conditions and material characteristics, they created both 1D and 3D models. Significant 3D effects were observed in the investigation, particularly for larger pile diameters, which could lead to misinterpretation if only 1D theory is employed. It demonstrated how FEM can enhance pile integrity assessments by providing recommendations for reducing 3D impacts [38]. Dina M. Ors et al. created a 3D nonlinear FEM model for laterally loaded piles in multi-layered soil profiles using ABAQUS software. The model considered complex relationships such as non-linear soil behavior, reinforcement yielding, and concrete cracking, with error margins ranging from -1.09% to 9.75% [39]. Mahdi et al. used the FEM to model the response of laterally loaded flexible free-head piles in layered soil profiles. The FEM model represented the pile as a series of line elements with three degrees of freedom, while the soil was idealized into five layers. The model calculated the maximum lateral displacement and bending moment under lateral loading. The FEM's ability to capture complex soil-pile interactions was demonstrated [40]. Onyelowe et al. use numerical models such as the FEM and Finite Difference Method (FDM) in their study on soil constitutive relations in geotechnical engineering. FEM is useful for simulating complex soil behavior under loading conditions, including those that are hydro-, thermo-, and thermo-hydro-mechanical [41]. Oğuzhan Çetindemir reviews modelling options for seismic soil-pile-structure interaction, including direct and substructure methods, as well as simple and sophisticated modelling techniques. Soil characteristics have a considerable impact on earthquake damage, with radiation damping effects being particularly strong when structural periods are substantially shorter than the soil cut-off frequencies. However, resonance may enhance responses when structural and soil periods coincide. The decision between simplified and high-fidelity models is based on analytical goals, with OpenSees offering improved boundary elements and contact modelling capabilities for complicated structures. Proper mesh sizing, soil constitutive models, and spatial ground motion variation are all important considerations; however, computational approaches are inaccurate and subject to inherent uncertainties [42]. O˘ guzhan Çetindemir, and Abdullah Can Zülfikar validate newly created elements in OpenSees for fully coupled seismic soil-pile-structure systems. New elements in the OpenSees collection require evaluation, particularly for soil-pile-structure interaction (SPSI) problems. This study highlights the significance of confirming these factors to close knowledge gaps [43].

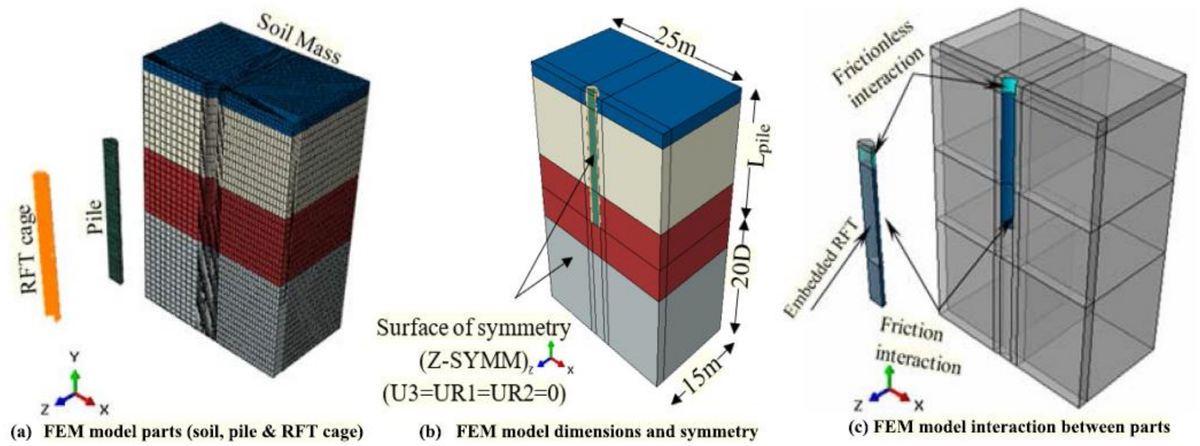


Fig. 15: Modeling concrete piles using FEM [39] **.**

5.8. Machine Learning Methods (ML)

In interpreting PIT data, ML is an effective tool for enhancing regression analysis, defect detection, and signal classification, thereby facilitating accurate and reliable assessment. ML models offer several advantages over conventional techniques, including the ability to analyze complicated, noisy, and non-linear data produced during PITs. Different machine learning techniques are illustrated in the image, categorized by their approaches (knowledge-based, logic-based, statistical, mathematical, evolutionary, searching, and neural-based) and applications (decision-making, classification, regression, and optimization). Mohamed Y. Abdel-Kader et al. demonstrated the potential of artificial intelligence (AI) in infrastructure projects analysis of research conducted between 1990 and 2021. AI techniques are classified into four categories: Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Fuzzy Logic (FL), and Artificial Neural Networks (ANN), based on their applications in various systems, including communication, gas, water, transportation, and electrical systems. They emphasize how AI can manage fuzzy, complex, non-linear data [44]. For instance, statistical techniques such as Support Vector Machines (SVM) and k-nearest Neighbours (KNN) are frequently employed in PIT data analysis for regression and classification. ANN and Deep Learning (DL), two neural network-based techniques, are particularly effective at automating the detection of flaws and modeling complex correlations in PIT signals. The interpretation models are optimized using evolutionary and search-based techniques such as Particle Swarm Optimization (PSO) and GA. The variety of (ML) techniques for enhancing pile integrity evaluation is illustrated in Figure 16, which provides a comprehensive mapping of these approaches and their potential applications. Ebid's study explores the use of AI techniques in geotechnical engineering over the past 35 years. The research, which focuses on AI methods such as ANN, GA, and SVM, addresses problems including soil property prediction, slope stability analysis, soil classification, and dynamic behavior modeling. Ebid highlights the rapid growth of AI in geotechnical applications and its potential for complex, non-linear problems [45].

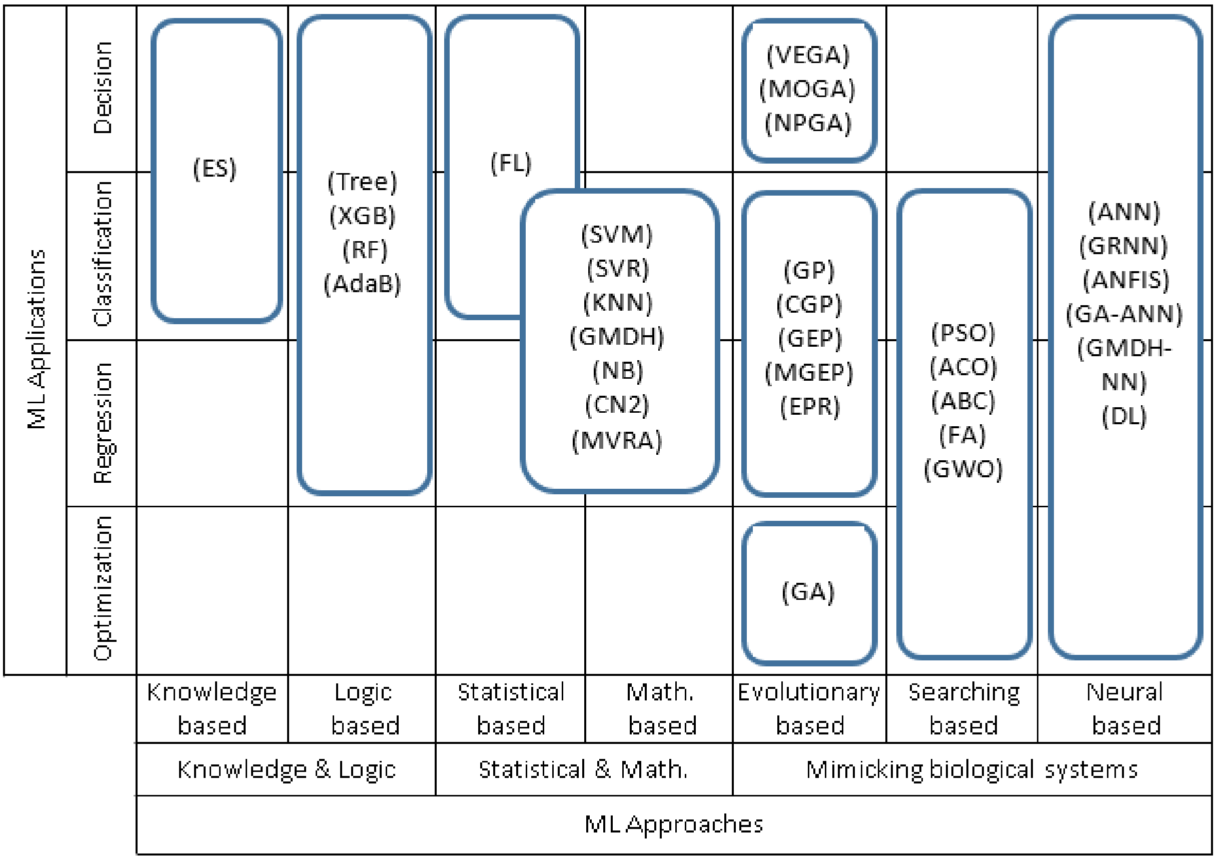


Fig. 16: Mapping for the commonly used ML techniques in (Application–Approach) space

Watson utilized ANNs to analyze low-strain test data to evaluate the integrity of cast-in-situ piles. Three types of neural networks—Multilayer Perceptrons (MLP), Radial Basis Neural Networks (RBNN), and Wavelet Basis Neural Networks (WBNN)—are recognized, assessing their efficacy in identifying and characterizing pile flaws. A significant advancement is the creation of a new wavelet-based preprocessing technique, known as the "wavelet mobility scalogram," which enhances the identification of pile head faults [46]. Liu et al. focused on a convolutional neural network (CNN)-based methodology for implementing pile integrity classification, thereby overcoming the drawbacks of conventional manual techniques, including high costs, inefficiency, and subjectivity. A dataset of low strain reflected wave images was enhanced, and a CNN model was trained, including four convolutional layers, pooling layers, and fully connected layers, with dropout and weight decay implemented to reduce overfitting. An average accuracy of 98.58% was reached across four pile integrity classifications (intact, slightly inadequate, severely defective, and broken piles) [47]. Wang et al. discussed the combination of RNN and multi-layer neural networks

(MLNN) methods to adequately classify pile integrity using low-strain pile testing data, thereby improving the sequential and temporal interactions essential to the signals. Concrete model piles were constructed for testing, and the data collected were classified into 13 unique categories, affecting differences in pile integrity from entirely adequate to severely inadequate piles. Ten-fold cross-validation was employed to enhance model performance, resulting in a classification accuracy of 98.46% on the test data. This effective method reduces dependence on subjective manual interpretation [48]. Meng et al. demonstrated a novel technique for assessing pile integrity by integrating analytical techniques with an ontology-based system known as OntoPIE. Conventional approaches that rely on qualitative metrics and subjective assessments have been replaced by a quantitative framework that utilizes elastic wave propagation and numerical fitting to examine velocity response curves for defect detection. Ontology modeling integrates with the Semantic Web Rule Language (SWRL) to facilitate accurate, automated assessments of pile flaws, including depth, length, and severity of problems. The system's accuracy was confirmed using case studies that compared inferred indications with established defect data, reaching findings within a 5% margin of error. This system provides faster and more precise pile evaluations, facilitating numerous applications in structural health assessments. These methods utilize various techniques, including finite element analysis, wave propagation, advanced testing, and data integration frameworks [49]. Protopapadakis et al. discussed an innovative defect detection system that employs neural networks focused on an island genetic algorithm. Low-strain integrity tests (LST) are modeled with a coupled finite element and scaled boundary finite element method (FEM-SBFEM) to produce numerical data representing actual pile fault scenarios, including necking and bulging. A classification model is developed by extracting information from the oscillation patterns of simulated pile waveforms to identify and locate flaws. High defect recognition rates were achieved, particularly for z-axis oscillation measurements, utilizing an efficient model that required minimal training data [50]. Onyelowe et al.'s study highlights the use of AI optimization techniques in geotechnical engineering, including Artificial Neural Networks, Genetic Algorithms, Fuzzy Logic, and Adaptive Neuro-Fuzzy Inference Systems. These techniques help predict soil behavior, optimize earthwork designs, and model settlement and pile resistance. They reduce reliance on laboratory testing and improve precision and sustainability in geotechnical engineering practices [51]. Shaoqiang Guo et al. utilized statistical techniques and AI to predict the dynamic characteristics of sedimentary rocks, including compressional and shear wave velocities. They used models like support vector regression, adaptive neuro-fuzzy inference systems, and BPANN. Time- and money-efficient forecasting models are demonstrated with SVR, which shows the highest accuracy. This technology has significant applications in rock and geotechnical engineering [52]. P Burrascano et al. describes a novel strategy for non-destructive examination of concrete piles based on wave propagation techniques. It uses reflected wave signal analysis and convolutional neural networks to classify pile integrity automatically. This strategy enhances efficiency and addresses uncertainty in manual interpretations, leading to increased reproducibility and accuracy. The inclusion of this paper in the review emphasizes the growing importance of AI-based approaches in structural diagnostics [53].

6. Discussion/Conclusions

Understanding how each technique addresses specific gaps in test procedures, equipment, and costs is crucial when assessing different pile testing methods, such as the ultrasonic pulse test, the pile integrity test (low strain), cross-hole sonic logging, the rapid pile load test, and the dynamic (high strain) pile load test. High-strain PDA testing has gained popularity in confirming the load capability of piles. PIT assesses the shaft's entire cross-section and profile, while CSL only assesses the concrete between access tubes. PIT only provides depth and an approximate estimate of defect extent, while CSL can estimate depth, horizontal location, and flaw extent. PIT is unreliable due to differences in concrete wave speed. Because the High Strain Method is more expensive and requires specialized personnel and heavy equipment, it is often used only for a smaller subset of piles that require in-depth analysis. However, Low-Strain Testing is a more cost-effective choice, which makes it suitable for evaluating many piles or all the piles in a project. Furthermore, low strain testing has advantages; yet their effectiveness may decrease with increasing pile depth or complexity. These approaches can be enhanced by other techniques or by combining PIT with CSL or numerical simulations. Additional testing, such as the High Strain Method or other techniques can be carried out on suspect piles using Low Strain Testing to confirm results or determine whether replacement is required. RPLT offers an intermediate approach by integrating static and dynamic testing elements to evaluate pile load capability, eliminating the need for extensive static testing or heavy dynamic loading equipment. The dynamic load test is reliable and valid and facilitates a rapid assessment of pile capacity compared to static load tests. It allows for testing one or more piles daily, as required by the project. Loading tests on single piles are conducted at a rate of one test for every 50 single piles, with a minimum of two tests, and nondestructive testing is performed on all single piles. For each site, at least one pile test is conducted for every 100 piles. For foundations with a single pile per column, at least two tests are required. The number of tests can increase based on project requirements, considering the arrangement and design factors of the pile group. Dynamic load testing on piles ensures the chosen weight and diameter are suitable for piles with capacities of up to 2000 tons. The results ensure that the applied loads do not exceed 50%-75% of the ultimate load capacity, thereby guaranteeing structural safety and proper performance. Selected piles undergo dynamic tests to confirm design assumptions and structural adequacy. Load tests on working piles, known as contract piles tests, validate design and execution by applying loads exceeding the design load by 50%-100% without causing collapse. This ensures consistency and reliability across the project by sampling at least one pile for every 200 piles. The testing frequency varies depending on the load test, as outlined in Eurocode 7. For static load tests, ultimate design requires a maximum of 1% or 0.5% of the piles, whereas serviceability design permits a maximum of 2% or 1% of the piles. Rapid and dynamic impact load testing have identical limits: a maximum of 3% or 1% of the pile's weight for ultimate control and up to 6% or 5% for serviceability control. These percentages typically apply to groups of piles under similar ground conditions and aim to ensure structural assessment and long-time performance. NDT methods provide a framework for assessing the integrity of piles. Fourier Transforms, and HHT isolate anomalies from noise in nonlinear, non-stationary data, improving fault identification—probabilistic approaches in reliability-based analysis account for load, resistance, and soil variability to create safer designs. In larger-diameter piles, the FEM accurately analyses stress-strain. It reduces misunderstanding by capturing complicated soil-pile interactions and 3D effects. Time-domain and frequency-domain methods facilitate the identification of defects, estimation of pile length, and evaluation of wave propagation patterns. ANNs and SVMs automate defect identification, regression, and classification in ML, improving NDT. NDT improves diagnostics, structural safety, and evaluation procedures, making pile integrity testing and fault identification essential.

The results of this overview can be summarized in the following points:

- The wave propagation-based pile tests are classified into low-strain and high-strain tests as follows:
  - Low-strain tests, usually used to detect defects that occur during concrete casting
    - PIT test, performed from the surface to detect length, necking & discontinuities.
    - CSL test, conducted along the pile to detect internal defects.
    - UPV test, used along pre-cast piles to check quality before driven.
  - High-strain tests, usually used to verify the axial compression capacity of the pile
    - DPLT impacts the pile with a limited-weight hammer, a fast test, but needs calibration with a static pile load test.
    - RPLT has a slower loading rate than DPLT, using an explosion or hammering on a rubber cushion; its results are closer to those of a static pile load test than those of DPLT.
- The commonly used interpretation techniques could be classified to analytical, reliability, numerical and machine learning based techniques as follows:
  - Analytical based techniques, depend on decomposing the signal into a set of simple components
    - Frequency-domain analysis extracts the amplitudes of different frequencies using FFT
    - FAT detects the amplitude of the first wave to assess the signal quality
    - NAL studies the radial propagation of the wave
    - HHT decomposes the signal into a set of waves starting with the highest frequency and down to the residuals.
  - Reliability-based techniques consider the impact of variation in pile dimensions and material properties on the signal analysis.
  - Numerical-based techniques, construct numerical models for the pile and the surrounding soil to simulate the system behaviour under testing conditions
    - NewMark's β method presents a simplified numerical differential formula for wave propagation
    - FEM, a well-known numerical technique to solve complicated differential equations. It can handle complex geometry and non-homogeneous materials but needs experimental verification.
  - ML-based techniques, which are new and innovative, depend on learning from existing databases experimentally or numerically. They offer more straightforward and more user-friendly alternatives, but these models are valid only within the parameter ranges considered during learning.

- The study indicated a shortage in ML implementation in interpreting the results of quality control tests for concrete piles; hence, further studies are recommended to develop more advanced ML-based models to interpret these test results.
- The scope of this research was limited to concrete piles; further research should be conducted for other types of piles.

Data availability:

This manuscript does not report data generation or analysis, so for more information, please contact the corresponding author

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