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Use of longitudinal wave in non-destructive methods: approach to foundation and retaining elements

Isabela Grossi da Silva[1#], Vítor Pereira Faro[1]

Review Article

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Abstract

Non-destructive tests (*NDT*) are used to verify the length or integrity of elements embedded in soils or rocks. These elements can be piles in foundations or nails and tiebacks in retaining walls. *NDT*s differ by the types of waves, ways to generate and receive the signal and to analyze data. Tests using sonic wave do not require a pre-installed pipe or wire and they are based on acoustic impedance theory. Despite its dissemination on piles, the application in retaining elements is recent and requires more studies to increase knowledge about these methods. This paper aims to present studies of sonic wave methods in foundation and retaining elements, presenting results, similarities, and differences. Studies from different dates are presented with their relevance, considerations for the different types of elements tested, objectives and methodologies used, to evidence the variables involved within this solution. The sonic test in foundation is widespread and has a greater number of studies. Withing this paper, the variables that interfere in the results of these methods were observed: the velocity of propagation of the sonic wave, the soil stiffness, the location of wave generation and reception and the type of hammer used, evidencing the necessity of further studies, especially in retaining elements.

1. Introduction

Buried elements such as piles, nails and tiebacks need special techniques to be inspected, so, a non-destructive or destructive methods are used. Destructive methods, among them the most known is the pullout test, have elevated cost, high execution time and it disables the tested element (Zima & Rucka, 2017). On the other hand, non-destructive methods (*NDT*) have faster execution time, relatively low cost per element, portability of equipment and the possibility to test all elements, since they do not damage the structure (Jayawickrama et al., 2007). Thus, the *NDT* becomes a good alternative to evaluate the integrity of elements embedded in the soil, besides allowing the verification of their lengths when there is no geotechnical project or to verify the execution of the project.

In the bibliography, there are several non-destructive tests, such as Sonic Echo (Cheung, 2003), Impact Echo (Carino, 2001), Impulse Response (Liao et al., 2008), Crosshole Sonic Logging (Jayawickrama et al., 2007), Time Domain Reflectometry (Lee & Arup, 2007), Parallel Seismic (Olson et al., 1998), and others. They are distinguished by the wave used, by its frequency, if it is necessary or not pre-installed elements and how the signals are obtained or interpreted. For example, the Sonic Echo, Impact Echo and Impulse Response methods are sonic methods that have acoustic impedance as a principle, but they are different by the way the wave is generated or how the data is interpreted. Crosshole Sonic Logging is an ultrasonic test that requires pre-installed tubes. Time Domain Reflectometry uses an electromagnetic wave and a wire that must be inserted during the execution of the element that serves as a reference for this method.

The use of non-destructive techniques is widespread in the context of foundations, with a large amount of works and the most known method is the Pile Integrity Test (*PIT*). On the other hand, in retaining walls, such as soil nail and tieback elements, the application is recent and it is necessary more studies to better understand the peculiarities of these methods.

The sonic methods, such as Sonic Echo (*SE*) and Impulse Response (*IR*), use longitudinal mechanical waves to interpret the results and have the main advantage that they do not need pre-installed tubes or wires to its execution. Thus, elements can be tested even if this was not planned during their execution. These techniques are based on acoustic impedance for the interpretation of results and they have some variables involved.

This article aims to present studies on low strain sonic methods in foundation and retaining elements, presenting a critical analysis of their results, similarities and differences between the method due to the elements tested.

[#]Corresponding author. E-mail address: isa.grossisilva@gmail.com
[1]Universidade Federal do Paraná, Programa de Pós-Graduação em Engenharia da Construção Civil, Curitiba, PR, Brasil.

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2. Theoretical background

This item presents the topics that explain how it works and which variables are involved in the use of sonic methods, which have the same theory for application in foundations and retaining walls.

2.1 Theory about sonic methods

The sonic methods use the acoustic wave, also known as shock wave or stress wave (Cheung & Lo, 2005) and they are based on acoustic impedance theory and these tests differ from each other in the way they are generated and interpreted. The acoustic wave has a frequency audible by humans, with values between 20 Hz and 20 kHz. Sonic techniques have as their principle the generation, transmission and reception of the acoustic wave in the element, which travels through it without generating reflection until it finds a section of discontinuity or change of physical properties, which causes the wave's reflection (Cheung & Lo, 2005). The equipment for these low strain tests, as they are also known, currently consists of a 1.5 kg hand hammer, a geophone or accelerometer-type signal receiver and a data acquisition device connected to a portable computer (Gong et al., 2006; Ni et al., 2006).

Jayawickrama et al. (2007) argue that the wave propagates in the element until there is a change in impedance, which may present partial or total reflection, and the reflected part is captured by the receiver. Thus, the impedance is generated when there is a change in the physical environment through which the wave travels, this change can be either in the resistance of the material or in the cross section. The impedance depends on the combination of the cross-sectional area, the modulus of elasticity and the density of the material tested (Thilakasiri, 2006), as shown in Equation 1. Where: Z = acoustic impedance (kg.m^{-2}.s^{-1}); A = cross-sectional area (m^2); E = Young's modulus of the material (Pa); ρ = specific mass of the material (kg/m^3).

$$Z = A\sqrt{E.p} \tag{1}$$

The reflection is captured by the receiver and can be difficult to differentiate the main reflection, referring to the toe element, from the other reflections, caused by variation of the element cross section and by different material existing in the length of the element (Lo et al., 2010).

Some considerations are made in relation to the sign direction of reflection captured by the receiver. According to Thilakasiri (2006) and the Brazilian Association of Non-Destructive Testing and Inspection (ABENDI, 2016) the sign direction of reflection is associated with impedance, which remains the same direction when there is a reduction in impedance and it becomes opposite when there is an increase in this variable. To exemplify, if the reflection from the toe element presents the opposite direction to that of the initial pulse, then it is fixed in a material of higher impedance, that is, more rigid. Regarding the reflections captured before the toe element, if it has the same direction as the initial pulse, it suggests a decrease in impedance, which may be a reduction in the section or in the stiffness of the material and if there is an increase in the impedance, the direction will be opposite. An example of a result by Sonic Echo method is presented in Figure 1 where a reflectogram is exhibited in time domain.

2.2 Variables involved in sonic method

The variables considered capable of interfering in the sonic tests are presented in more detail in this item, which are: the wave velocity, the ground stiffness, the place of generation and reception of the wave and the tip hammer to create the shock wave.

2.2.1 Acoustic wave velocity

The waves originated in sonic methods are considered low strain and propagate as elastic waves, also called mechanical waves. Mechanical waves need a medium to propagate which happens in a three-dimensional way. The propagation velocity is a characteristic of the medium and it is independent of the wave frequency created, so it is a medium constant.

Finno et al. (1997) presented that, in general, there are three types of waves generated from the stress wave, they are: primary waves (*P* waves), secondary waves (*S* waves) and Rayleigh-type surface waves (*R* waves). However, as in sonic tests the P wave has a higher velocity than the others, it is identified more clearly and is used to determine the length of the elements.

P waves are called primary, compressional or longitudinal and their velocity can be calculated as shown in Equation 2 (Lee, 2017). Where: V_p = primary wave velocity (m/s); E = Young's modulus of the material (Pa); ρ = specific mass of the material (kg/m^3). In this way, a stiffer material

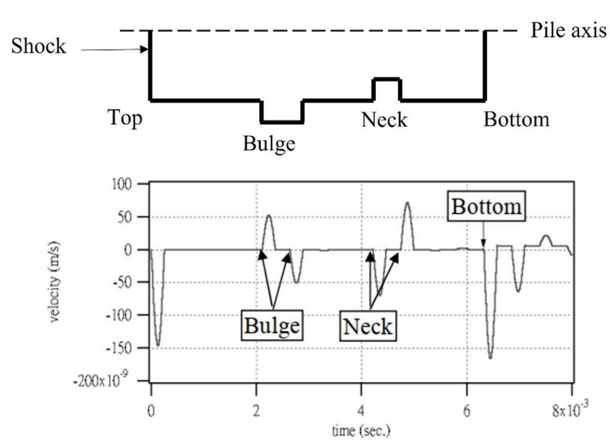

Figure 1. Reflectogram in time domain from SE method [adapted to Lai et al. (2006)].

will have a higher velocity in relation to another with less stiffness, if the same specific mass is maintained.

$$V_p = \sqrt{\frac{E}{\rho}} \tag{2}$$

The *S*-wave, called secondary, shear or transverse, can have its velocity calculated according to Equation 3 (Lee, 2017), where: V_s = secondary wave velocity (m/s); G = material shear modulus (Pa). In this case, the particle moves perpendicularly to the direction of wave propagation. Also, according to Probst (2013), this type of wave propagates only in solid elements, since liquid and gaseous media do not support shear forces.

$$V_s = \sqrt{\frac{G}{\rho}} \tag{3}$$

As known, Young's modulus and shear modulus are related through Poisson's ratio as described in Equation 4. Where: ν = Poisson's ratio. Poisson's ratio can have a value between 0 and 0.5 in the case of an elastic material, but in the case of steel, grout and soil it has a value around 0.2 to 0.3. Thus, following these values, the shear modulus results between 0.42 and 0.38 of the Young's modulus and the shear wave velocity becomes something between 0.65 and 0.62 of the longitudinal.

$$G = \frac{E}{2(1+\nu)} \tag{4}$$

The Rayleigh wave (*R* wave) propagates along the material surface and has a decreased amplitude as it permeates. This wave results from the interference of *P* and *S* type waves, causing vibrations in the opposite direction to the wave propagation. As exposed by Finno et al. (1997), its velocity can be calculated by Equation 5 which correlates it with the velocity of the shear wave, where: V_r = Rayleigh wave velocity. By this equation it is verified that, if the Poisson's ratio is considered variable from 0 to 0.5, the velocity of the Rayleigh wave is 0.862 to 0.955 of the shear wave.

$$V_r = \frac{0.862 + 1.14\nu}{1+\nu} V_s \tag{5}$$

By the Equations 2-5, it can be concluded that the propagation velocity of the types of waves decreases in the order: $V_p > V_s > V_r$.

When the element length tested is known, it is also possible to calibrate the velocity wave V through Equation 6. Where: L = length of the element and $2L$ refers to the way traveled by the round trip of the wave (m); t = time between generation and receipt of wave reflection (s).

$$V = \frac{2L}{t} \tag{6}$$

When analyzing Equation 6, it is observed that if the velocity varies by 10% from its presumed value, it will reflect in a direct variation of 10% in the length of the element. However, as the length of the buried elements in the soil is, normally, one of the parameters that is wanted through the test, this verification is not always possible to be carried out, making it of greater use in laboratory calibration tests.

The wavefront geometry is another characteristic that can qualify acoustic waves, it can be planar or circular. The planar geometry waves have the wavefront located in a plane that propagates in a space and the circular waves, which occur in 2D elements; or spherical, which occur in 3D elements, propagate symmetrically around a reference point (Azhari, 2010). The wavefront geometry can be impacted by the dimensions of the element in which it propagates and affect the results obtained in the sonic tests.

In sonic tests, the ability to detect defects depends on the wavelength, frequency of the wave and the size of these fails. The wave propagated in the element will reflect upon encountering an anomaly when its wavelength is shorter than the defect (Finno et al., 1997). Finno et al. (1997) expose Equation 7 which correlates the wavelength $\boldsymbol{\lambda}$ (m) with the frequency f (Hz) and the propagation velocity of the wave V_p (m/s).

$$V_p = f.\lambda \tag{7}$$

The authors showed that in the case of a concrete with a propagation velocity of 4000 m/s and the hammers tip that generate a frequency from 0 to 2000 Hz, then the shortest wavelength is 2 m. Andreucci (2018) emphasizes that it is essential to know the wavelength, as it is directly associated with the size of the defect to be detected. Thus, using low frequencies reduces the sensitivity of the method.

2.2.2 Soil stiffness

Thilakasiri (2006) says that in the graphs of low strain methods it is common to observe positive or negative reflections that are not caused by the impedance change of the pile axis, but rather from the stiffness of the soil layers present along the element. The amplitude of the reflection referring to the analyzed defect is reduced with the increase of the soil stiffness (Huang et al., 2010), in the same way the toe reflection can be difficult to identify due to the high stiffness of the soil. Liao et al. (2008) reiterate that it becomes more uncertain to determine the location of the toe element or the anomaly, the closer is the element stiffness and the ground. It is noted that when the tested element is included in the ground, there is radiation from the waves that are propagated along this element. The main consequence of this effect is an increase in the damping of the wave, making its reflection more difficult to detect (Ambrosini & Ezeberry, 2005).

Due to the influence of this variable, the operator may misinterpret the result by considering that some reflections are related to the change in impedance caused by the variation of the cross section, when in fact it refers to the change in stiffness of the soil that the element is included in (GDFC, 2000; Thilakasiri, 2006). However, Thilakasiri (2006) observed in his study that the reflections from the variations of the soil layer along the element are characterized by having relatively small magnitude and greater pulse width when compared to the reflections due to axis defects.

2.2.3 Local of impact and receiving signal

Sonic methods may present variations in the location of the accelerometer and the local of generation of the acoustic wave, this characteristic influences the result and it is more deeply studied in piles (Chow et al., 2003; Wang et al., 2014; Zheng et al., 2015), but it also interferes in nails, as reported by Jayawickrama et al. (2007). Studies show that this variable must be considered in the interpretation of the result, because depending on the material present in the local of generation and reception of the wave and the distance between these two points, there may be greater damping of the wave, greater presence of noise in the generated signal and greater difficulty in interpreting the results.

2.2.4 Type of hammer used to generate the wave

Another possible variation is to use different tips in hammers with different materials stiffness for better detection of length or defects in the tested element. Many authors (Finno et al., 1997; Cheung & Lo, 2005; Liao et al., 2008; Rashidyan, 2017) cite that hammers with different tips materials and, consequently, different stiffnesses affect the impact duration that create waves with varied characteristics, modifying the wave frequency and wavelength traveled by the tension wave.

According to Jayawickrama et al. (2007), soft tip hammer generates a low frequency wave despite a longer wavelength, traveling greater distances with less attenuation. However, loss of accuracy occurs for small defects, and it can be used with better results for the element length detection. In opposition to this, the hammer with a stiff tip produces a wave of higher frequency and shorter wavelength, creating a greater dissipation in its trajectory, but it has good results for the identification of small failures. Thus, the use of both types of hammers is ideal for detecting the length of the element, small and large defects at different depths.

Davis (2003) says that tension levels range from 5 MPa for rubber tip hammers up to 50 MPa for aluminum tips. It is important to know the magnitude and duration of the hammer induced pulse. For Ambrosini & Ezeberry (2005) better results are obtained when high energy levels are incorporated in as little time as possible. This characteristic results from stiff tips.

Kirsch & Plaβmann (2002) expose hammers with tips of different materials, producing different forces and contact time. The use of the iron hammer produces greater force intensity and shorter contact time when compared to the rubber hammer. It is observed that the curves presented have the shape of a symmetric Gaussian.

2.2.5 Advantages and limitations

Regarding the *PIT* and Sonic Echo assays, one of the main advantages presented in the bibliography (GDFC, 2000; Cheung, 2003; Ni et al., 2006; Jayawickrama et al., 2007) is related to the test execution speed, being possible to test several elements in just one day, reducing the cost of the test per element. For this reason, this technique has great acceptance in the market. In addition, the authors cite the advantage of no need pre-installed pipes in the tested elements (GDFC, 2000; Lee & Arup, 2007; Ozyildirim & Sharp, 2012) and the ease of application of the method since it is only necessary to have access to the element head to perform the test (GDFC, 2000; Cheung, 2003; Lee & Arup, 2007).

Furthermore, there is a limitation discussed among the authors associated with the maximum length/diameter (*L/D*) ratio of the element for which there is a wave signal and acceptable results are obtained from the element. This relationship tends to be considered as a general rule for the decision to perform sonic tests on piles and often on nails. Jayawickrama et al. (2007) state that for stiff clays, the average *L/D* ratio tends to be 30/1 and for soils with low Young's modulus, results up to 50/1 can be obtained in the same way. ABENDI (2016) ensures that the maximum *L/D* ratio is between 30/1 and 50/1. Huang et al. (2010) consider that the maximum *L/D* ratio depends on the soil stiffness around the nail and it is between 10/1 and 32/1. The tests carried out by Lee (2017) in their research tested elements with L/D between 10/1 and 70/1 and the author considered the results satisfactory. GDFC (2000) and Likins & Rausche (2000) argue that the 30/1 ratio is commonly cited as limiting, however, the last authors elucidate that with recent electronic techniques, leading to lower noise and therefore this relationship can be higher. Ambrosini & Ezeberry (2005) studied piles with a *L/D* ratio of 40/1 and concluded that the results were satisfactory. Klingmüller & Kirsch (2004) and Ni et al. (2006) claim that the low strain method has an accuracy of ±5% in determining the length of the tested element and GDFC (2000) comments that the accuracy of the method for defect location is between 5 and 20%.

This method is highly dependent on the professional's experience for the execution and interpretation of the results, as commented by Cheung (2003), Cheung & Lo (2005), Hertlein & Davis (2007) and Rashidyan (2017).

3. Discussion

In this item, studies from different periods are discussed exposing their relevance and conclusions. They were chosen to present studies and considerations on the different types of elements, such as piles and nails. This research presents varied objectives and methodologies, including laboratory tests, field tests and/or numerical modeling, in order to cover the different variables involved. With this result exhibition it is possible to observe characteristics, differences and similarities of the tests in the different elements.

3.1 Studies on foundation elements

Seitz (1985) says that the low strain method may be limited by the length/diameter ratio and by the wave dissipation caused by soil resistance or concrete damping. The author also reports it is necessary skilled labor to carry out the test and the data interpretation. Low strain tests were carried out on a pile cast in place using vibrating equipment and the wave propagation velocity obtained was between 3900 and 4700 m/s, with an average value of 4000 m/s. For large diameter drilled piles the average velocity was 4230 m/s and 4200 m/s for piles excavated with bentonite mud.

Chow et al. (2003) studied the effect of three-dimensionality in piles, as they observed that although the one-dimensional theory can be and is widely used in these elements for the interpretation of results, in cases where the hammer diameter is too small in relation to the pile diameter, it can result in a misinterpretation of the results. The authors show as an example a hammer with a diameter of 4 to 5 cm and a pile with a diameter of 1.60 m, so the pile would have a diameter between 32 and 40 times greater than that of the hammer. Inadequate interpretation is due to the fact that, when analyzing the problem in 3D, the initial impact response generates an opposite signal peak right after this first peak, this is due to the proximity between the impact site and the receiver. Thus, this reflection can be interpreted as an anomaly near the head of the pile. This error can be avoided by keeping a distance greater than 50% of the pile radius between pulse generation and reception according to the authors.

Chai et al. (2010) modeled a pile in a finite element software to study an optimal position for locating the receiver, in which the generated surface responses have less disturbance caused by the multireflections of the *P*, *S* and *R* waves on the side surface of the pile. The authors state that when the characteristic wavelength is relatively large, that is, the impact contact time is at least four times the pile radius divided by the propagation velocity of the stress wave, the waves that are far from the top of the pile are little affected by the wave's source radius and their behavior is dominated by the longitudinal wave propagation mode, approaching plane waves with little dispersive behavior. Furthermore, it is recommended that the results be analyzed by the one-dimensional wave theory only when the defects are located at a depth greater than twice the diameter of the pile in relation to the element head, when the characteristic wavelength is relatively large and when the receiver is coupled to about 60% of the pile radius in relation to its axis.

Lo et al. (2010) tested bridge foundations with the Sonic Echo method. They found errors of 8.0 to 9.1% in the length of the elements, and they warn that the wave reflection at the toe element is not always easy to identify due to the noises picked up. The authors obtained the velocity of the stress wave in the concrete, considering a specific mass of 2400 kg/m^3, can vary from 2000 to 4500 m/s depending on its quality.

Cosic et al. (2014) modeled a 2D and 3D pile with discontinuities and defects simulating a *PIT*-type non-destructive test to examine how the generated reflectogram behaves. For this, first, an integrated pile was modeled as a comparison in relation to the others with defects. The simulated anomalies were piles with defects near the head of the element, impedance reduction along the pile, piles with shorter and longer length than the intact pile and piles with weak reflection at the toe element. It was possible to clearly perceive the difference produced by the different elements in a satisfactory way. The study also created results with the change of the Young's modulus of the soil around or below the pile together with simulations of defects in different locations. It was observed that when the modulus of elasticity of the soil below the pile was too high (10 GPa), the tip reflection was deficient when compared to the other values tested (1 GPa, 500 MPa, 250 MPa, 100 MPa, 50 MPa and 1 MPa). When different Elasticity moduli of the soil around the pile were simulated, it was found that the greater the stiffness of the soil, the lower the tip reflection, and the value of 10 GPa produced great reflection along the entire length of the element and little toe reflection, making it difficult to identify. In addition, different result acquisition sites were tested for the same impact region. These locations varied symmetrically and were simulated in the intact pile and with defects. In the intact pile, the local where the result was obtained did not influence the response and, for piles with defects, the results varied.

Wang et al. (2014) modeled a pile in order to analyze the difference produced in the reflectograms about the initial impulse width, the data acquisition point and the soil Young's modulus were varied. The modeled pile was 16 m long and 1 m in diameter. Pulses with a width of 0.5, 1.0, 1.2, 1.5 and 2.0 ms were also tested, and the pulse that generated the best result, that is, greater tip reflection, was the one with the greatest width (2 ms). In addition, different location distances of the signal receiver were simulated in relation to the center of the pile, as in the center of the element, in ¾ of the radius, ⅔ of the radius and ½ of the radius. Data acquisition points between ⅔ to ¾ of the radius were considered the most suitable for concrete piles, but in reinforced concrete piles, the best distance for data acquisition was ⅔ of the radius, because if the signal is received close to ¾ of the radius the result may have interference from steel vibration.

Wu et al. (2015) tested three types of non-destructive tests on six piles with pre-installed damage and the results for the Sonic Echo test, which is the objective of the present study, are presented below. First, the six piles without the block above their head were tested. The first pile was designed to be the reference pile, that is, without defect. In this case, it was possible to identify the tip reflection and estimate the length with an error of only 3.33% using the average wave velocity of 3000 m/s. Four piles were simulated with minor defects, in which the tip reflections were identified, resulting in the element length very close to the real one. In the sixth pile, as it contained a more severe defect (rupture in the cross section of 20 mm), it was possible to identify only the location of the defect. The second test methodology was carried out after the execution of the block on the piles and it was concluded that they significantly interfere with the captured signal. The intact pile and the other four with minor defects still had the tip reflection identified, but the error was approximately 15% of the actual length and it was not possible to identify the location of the defects. For the element with the greatest damage, only the reflection of the defect was identified in the same way as in the previous test.

Zheng et al. (2015) analyzed the effects of the low strain test on piles through numerical modeling focusing on the optimal location of the receiver in relation to the pile radius. For this, they tested the distances of 20%, 40%, 60%, 80% and 100% of the pile radius in relation to its axis and concluded that the interferences captured by the receiver are minimal in 60% of the radius and most noticeable near the center and near the edge of the element. Thus, they defined that locating the receiver at a distance of 50 to 70% of the pile radius would produce the least interference in the results.

Jwary (2017) tested different non-destructive methods on wooden piles and the Sonic Echo technique was successful in 94% of the determinations and generated an accuracy of ±15% in the results. The author used four different hammer tips and the velocity found was around 4500 m/s, varying a little more or less depending on the hammer used.

Rashidyan (2017) listed some factors that can influence the Sonic Echo trial, explained the consequences and proposed corrective measures for each of them. Firstly, the impact can be weak or generated incorrectly, resulting in weak longitudinal waves, to avoid this, always hit perpendicularly to the element and with adequate force. The use of incorrect hammers can generate waves that do not reach the toe element due to the high frequency, short wavelength and high attenuation of the same, as occurs with hammers with more rigid points. The use of hammers with a more flexible tip generates waves of low frequency and great length that reach greater depths, but can be confused with reflections from defects in small depths. The author states that the correct choice of the best equipment depends on the judgment and experience of the operator. Soil resistance also influences the results, generating undue reflections that can be confused with a change in the impedance of the pile and attenuating the wave in a way that makes it difficult to interpret the test. Furthermore, the author explains that the wave propagation velocity is one of the test variables and, when erroneously estimated, causes an error in the location of the defect or in the determination of the length of the element. The author explains that large diameter piles can generate plane waves that propagate longitudinally along the pile axis and one way to avoid them is to make the wavelength greater than the pile diameter, however, if the pile diameter is too large, another non-destructive method is recommended. Another aspect that can hinder the performance of this technique is the existence of defects near the head of the element or the existence of multiple defects in depth. In addition, the author performed numerical modeling in which the presence of the anchor block and its shape, the location of wave generation, the duration and shape of the initial pulse were investigated.

3.2 Studies on retaining elements

Salloum et al. (2003) used the Impulse Response (*IR*) method to estimate the length of nails. They performed experimental tests and numerical analysis. The study showed that the length of steel bars and nails were easily determined with the *IR* technique. It is important to emphasize that the mechanical properties and the condition of the mortar dominated the behavior of this elements. The authors emphasize that knowledge of the longitudinal wave velocity of the mortar was the key parameter to obtain a reasonable estimate of the length of the nail.

Cheung & Lo (2005) studied different non-destructive methods to verify the integrity of nails installed on the ground. The authors mentioned that the propagation velocity wave in the mortar is between 3500 and 4000 m/s. The authors state that no significant interpretation could be performed, as there were considerable difficulties in identifying the wave reflection due to the presence of discontinuity in the mortar, that activities close to the site may have interfered with the results and that it is necessary to have an experienced person to conduct the test and interpreted the results.

Gong et al. (2006) carried out a preliminary survey of available non-destructive methods to choose which would be most appropriate for the intended study. In this case, the Sonic Echo and Impulse Response methods stood out. The authors argue that the Impulse Response method is more favorable for the detection of shallow defects. The authors built a soil nail containing 32 nails of different lengths, with pre-established defects, and used mortar and cement grout as a binder to wrap the steel bar. The average wave propagation velocity in the cement grout was around 3900 m/s with a standard deviation of approximately 14 m/s and for the mortar it was 4240 m/s with a standard deviation of 47 m/s. The Sonic Echo method proved to be effective in locating large defects at greater depths and in some cases identified minor fails.

Jayawickrama et al. (2007) studied different locations in nails for the generation and receipt of the acoustic wave, being carried out in the bar and/or in the cement grout. They concluded that the combination with both in the cement grout proved to be more effective to detect defects and their locations, however it is essential to have good condition of this material in the part close to the head of the nail, which becomes a great limiting factor. In the research carried out by these authors, nails were included in the soil of approximately 1.50 m to 7.60 m. For nails, the conclusions obtained are that with a maximum length of around 4.50 m, there was an approximation of the result between the real and measured lengths. For elements between 6.00 and 7.60 m, the values obtained had a greater distance from the projected ones and, therefore, it is a method that needs further study to prove total efficiency. Furthermore, two speeds were used in the graphs presented, 16000 ft/s (4877 m/s) and 16500 ft/s (5029 m/s), in 75 graphs presented in the study.

Liao et al. (2008) evaluated the Sonic Echo and Impulse Response method in nails exposed to different boundary conditions and the results were showed by graphs in the original paper. The authors calculated the propagation velocity in the steel resulting in 5095 m/s. For the test performed only with the steel bar in the air, the error was considered to be 0% and in the original paper, the graphs presented there is no wave attenuation. Another test was performed with the bar buried in the ground, in this case the error was 3%, but in the original paper it is observed that the curve has great damping due to the wave dissipation in the ground. A third case tested was nails from 1 to 6 m in length molded side by side, in this case it was difficult to identify the reflection corresponding to the toe element. The authors suppose that this difficulty is due to the similar stiffness value of the materials tested, a condition proven by impedance theory. The maximum error in this case was 52%. Two other nails were tested in situ, it was found that the recognition of the toe element was more complicated in this case and the errors were greater than the errors obtained in laboratory tests. For the 1 m bar the error was 7% and for the 4 m bar the error was 5%, which were considered low errors.

Liu et al. (2014) presented considerations about ultrasonic *NDT* in nails, which, despite not being the same technique studied in this work, has similar principles to the Sonic Echo and, therefore, its use was considered relevant. The authors performed laboratory tests and numerical modeling. Different materials with a diameter of 10 mm were simulated to verify their influence on the wave propagation velocity, obtaining a velocity of 4918 m/s for steel and 2294 m/s for mortar. One other simulation refers to steel bars with different diameters as 10 and 60 mm. The velocity varied although only the diameter was changed, this conclusion is not expected for the Sonic Echo. The velocity of the 10 mm diameter steel bar as mentioned was 4918 m/s and for the 60 mm bar 4491 m/s was obtained.

Lee (2017) tested nails fully filled with cement grout of 1, 3, 5 and 7 m in length, being the 7 m element the result of the coupling of a 5 m bar with a of 2 m. The velocity obtained was 3324 m/s and the sign of the reflection at the toe element was the same as the initial pulse due to the presence of material of equal or less rigidity at the bottom of the clamp. The coupler was identified by the author and the location shows the opposite sign to the impact due to the increase in stiffness and cross-section.

Zima & Rucka (2017) studied the ultrasonic test of guided wave propagation on tie rods. For that, they carried out numerical and experimental tests focusing on the recognition of the energy transferred between the tie rod components. The authors tested and modeled tie rods with different anchored lengths and mortar thickness. They analyzed how the guided waves propagate in the unbonded and bonded length, in the interface between the bar and the part with surrounding mortar, as well as the diffracted waves at the beginning of the element. With this study it was possible to conclude that the presence of the mortar in the anchored part of the tie-rod influenced the wave propagation velocity and the amplitude of the signals. The free and anchored length and the thickness of the mortar were determined based on the wave propagation signals recorded at the free toe element. It was possible to determine the mortar thickness based on the knowledge of the surface wave velocity and the time of flight between the diffracted wave (another ultrasonic technique) and the reflection of the external surface of the mortar.

Yu et al. (2018), first, tested in the laboratory steel bars, steel bars partially filled with cement grout of different lengths, then installed such elements in the soil and, in addition, tested elements already present in the field. Several results are presented in this article, but what stood out is that the velocities found in the nails tested in the laboratory were the same as when the nails were tested after being buried in the ground. The first test carried out used only steel bars with a length of 1, 2, 3, 5 and 7 m, being a single 5 m bar and another consisting of a 2 m bar coupled into another 3 m. The study presents such graphs, in which it is possible to identify the time referring to the toe reflection and to the place of the coupled, in the case of the 2 m bar spliced with the 3 m one. The sign of the impact and the toe element are the same as the bar is in the air and so there is no increase in impedance. However, the sign of the coupler location is opposite to that of the initial pulse, as there is an increase in impedance. In this case, a minimum velocity of 4975 m/s and a maximum of 5195 m/s were obtained. In the case of bars partially filled with cement grout, 3 m nails were tested without the presence of grout in the last 1.5 m and another with 4.85 m with 0.5 m of void in the middle of the element. In this case, more reflections are presented in the graphics, but the authors still identified the defect location and the toe element. The average velocity in the elements was 3489 and 4026 m/s, respectively. In the tests carried out with bars completely fully filled with cement grout and placed on the ground, single bar with 1, 3, 5 and 7 m bars were tested, and a 5 m bar coupled with another 2 m. In the graphs presented, the defect and the toe element were located, but there is great wave damping and the calculated velocities were between 3304 and 3618 m/s. The simulated bars with defects were placed on the ground, and it was possible to locate the anomalies, in the same way as the toe elements, there was great wave damping and the same velocities described in the case of the nails tested in air. The last test was to test nails in situ already installed on a slope and the minimum velocity was 3181 m/s and the maximum was 3324 m/s. A large amount of noise is observed at the beginning of the graph and it is possible to identify the length of the elements.

Silva et al. (2021) studied a new system to create the acoustic wave using a magnetic field to propel the mechanical wave-generating projectile in the element to be tested. With this, the shock for the generation of the mechanical wave has no operator interference and the wave is always generated with the same intensity and control in the place of generation and signal reception. Furthermore, the results reproducible is guarantee. The authors tested, in the laboratory, the new wave generation device in 1 m long bars, obtaining a velocity of 5172 m/s and an error of 0.74% for results analyzed in the time domain and of -0.19% when analyzed in the frequency domain.

4. Conclusion

Non-destructive methods emerge as an alternative for measuring the length and integrity of elements buried in soil, such as piles, nails and tiebacks. There are several types of these tests in the literature although this work has focused on the low strain tests which is known as Pile Integrity Test in foundation and retaining elements is subdivided into Sonic Echo and Impulse Response. These tests are based on the theory of acoustic impedance and as variables that interfere in the tests as: the propagation velocity of the sonic wave, the stiffness of the soil, the place of generation and reception of the wave and the type of hammer.

With the exposition of studies on sonic tests on foundation and retaining elements, it is observed that the propagation velocity of the sonic wave is a variable of great importance in determining the length and integrity of the objects tested and that it varies with the characteristics of the material and its quality (presence of voids) interferes with its value. Soil stiffness is another variable present, however it affects in a more accentuated way the tests in piles, since the predominantly horizontal stratigraphy of the soil causes greater variation of its stiffness in these vertically buried elements. When the tested element and the ground have similar stiffness, it is difficult to identify the reflections caused by the impedance variation. The wave generation and reception location are more studied in piles due to the greater transversal dimension of these elements, despite interfering in the result of both elements. The type of hammer is a factor that also deserves attention and presents studies in retaining and foundation elements, with the contact time and its material being decisive for the generated wave.

It is evident that the *NDT* can be used in foundation and containment elements and it is important to emphasize that they still need further studies and innovation both for their execution and for the interpretation of the techniques. After these approach about *NDT* using acoustic wave, the authors observe a variable which could be controlled. Looking for this subject, it has highlighted how about the experience operator can affect the generation of the sonic wave. In this way, the authors suggest studies to control the generation of the acoustic wave like related by Silva et al. (2021). With this conception is possible to control the local and intensity of wave generation, the results reproducibly is guarantee and a variable is deleted in the signal interpretation.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Isabela Grossi da Silva: conceptualization, data curation, visualization, writing – original draft. Vítor Pereira Faro: conceptualization, supervision, validation – original draft.

Data availability

No dataset was generated or evaluated in the course of the current study; therefore, data sharing is not applicable.

List of symbols

f	wave frequency
t	time between generation and receipt of wave reflection
A	cross-sectional area
E	Young's modulus or elasticity modulus of soil
G	shear modulus material
L	element length
V_p	primary wave velocity
V_r	Rayleigh wave velocity
V_s	secondary wave velocity
Z	acoustic impedance
IR	impulse response
NDT	non-destructive test
PIT	pile integrity test
SE	sonic echo
ν	Poisson's ratio
ρ	specific mass
λ	wavelength

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