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Identificação de tubulação de esgoto em estruturas de concreto via tomografia ultrassônica

Identification of sewer pipes in concrete structures through ultrasonic tomography

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RESUMO

A avaliação não destrutiva de estruturas de concreto tem sido amplamente utilizada, seja para verificar a deterioração do elemento ao longo do tempo, ou para identificar defeitos durante concretagem. Atenção especial tem sido dada a identificação da presença de tubulação de água fria e esgoto integradas ao elemento estrutural uma vez que sua presença pode interferir na performance do elemento. Assim, o objetivo desse trabalho é avaliar o uso da tomografia ultrassônica para identificar a presença de tubulação de esgoto de PVC em estruturas de concreto. O algoritmo de reconstrução tomográfico foi implementado em MatLab. Para verificar a efetividade do método, um corpo-de-prova de 20cm x 20cm x 20cm com um tubo de PVC interno de 10cm foi desenvolvido. Como forma de estudar a dependência de malha no método, malhas de 5cm x 5cm e 2.5cm x 2.5cm foram utilizadas. Gráficos de contornos foram utilizados para exposição dos tomogramas. Foi possível localizar e acessar informação sobre a geometria da tubulação. A dependência de malha tem influencia significante na representação geométrica do defeito. Menores malhas levam a melhores tomogramas. A tomografia ultrassônica em concreto tem potencial para ser utilizada na identificação de não homogeneidades em estruturas de concreto.

Palavras-chave: Concreto. Inspeção não destrutiva. Velocidade de pulso ultrassônico. Tomografia.

ABSTRACT

Non-destructive evaluation of concrete structures has been increasingly used, whether for checking the deterioration of the element over time or for identifying faults during concreting. Special attention has been given to the identification of water and sewer pipes integrated into the structural elements since their presence can interfere in their performance. Thus, the aim of this paper is to evaluate the use of ultrasonic tomography to identify the presence of PVC sewage pipes in concrete structures. The tomographic reconstruction algorithm was implemented in MatLab. To verify the effectiveness of the method, a concrete specimen of 20cm x 20cm x 20cm with an internal 10cm PVC sewer pipe was developed. In order to study mesh dependency, meshes of 5cm x 5cm and 2.5cm x 2.5cm were used. To display the tomograms, contours were used. It was possible to locate and get information regarding the geometry of the pipe. Mesh dependence has a significant influence on the geometric representation of the internal defect. Smaller meshes lead to better tomograms. Ultrasonic tomography in concrete has great potential to be used to identify non-homogeneities in concrete structures.

Keywords: Concrete. Non-destructive assessment. Ultrasonic pulse velocity. Tomography.

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1. INTRODUCTION

Non-destructive inspection of concrete structures has been increasingly used, whether for checking the deterioration of the element over time or for diagnosing faults during concreting. Special attention has been given to the identification of water and sewer pipes integrated into the structural elements since their presence can interfere within its performance (HAACH; RAMIREZ, 2016; PESSÔA *et al.*, 2016; REGINATO *et al.*, 2017a).

An alternative to identify the presence of hydro-sanitary pipes in concrete structures is the use of the ultrasonic pulse propagation test combined with a tomographic reconstruction algorithm (PERLIM, 2015; SACRAMENTO *et al.*, 2021). The ultrasonic tomography is a non-destructive evaluation method that combines a tomographic algorithm with ultrasonic readings in several directions to reconstruct internal sections of concrete structures. (CHOI; POPOVICS, 2015; HAACH; RAMIREZ, 2016).

With the use of ultrasonic tomography, it is possible to represent the interior of concrete structures without causing damage to the studied element. Furthermore, it is possible to identify the presence of pathologies, their geometry and measure the possible interference in the structural capacity (VONK; TAFFE, 2018; PERLIM, 2019).

Hence, the aim of this paper is to evaluate the use of ultrasonic tomography to identify the presence of PVC sewage pipes in concrete structures.

1.1 Basis of ultrasonic tomography

In a simplified way, the physical problem that governs the tomography is described in Fig. 1. The difference between the signal that leaves the source and arrives at the receiver provides the information about the interior structure of the body. Considering projections in many different directions, it is possible to reconstruct the internal characteristics of the object (DE PIERRO, 1990).

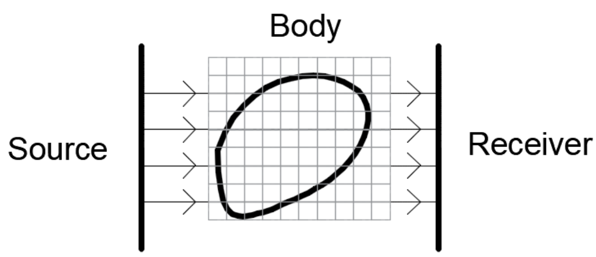

Figure 1. Scheme of the physical principle that governs tomography.

This is the basis of tomography and it can be expressed mathematically in the form

$$\Delta S = \int d_j a_j \tag{1}$$

where ∆S is the difference between the emitted and received signal, d_j é is the distance traveled by the signal in the infinitesimal element j, and a_j is the attenuation in the element.

In the ultrasonic tomography in concrete, the difference between the emitted and the received signal ∆*S* is the time *T* necessary for the ultrasonic pulse to be emitted from the emitting transducer, to pass-through the concrete body and to be received at the receiving transducer. The attenuation property a_j is the resistance that the material has in relation to the wave propagation velocity, and this can be expressed as

$$p = \frac{1}{V} \tag{2}$$

where *p* is known as pulse vagarosity, and *V* is the ultrasonic pulse velocity.

The elements d_j refer to the geometry of the body and mesh discretization. Thus, the equation that describes the travel time of the ultrasonic pulse in the concrete can be expressed as

$$T = \int_e^r p_j dL_j \tag{3}$$

where *T* is the travel time, p_j is the pulse vagarosity in element *j*, and dL_j is the traveled distance in element *j*.

The integral described in Eq. 3 can be numerically approximated for a summation using numerical quadrature methods (BURDEN; FAIRES, 2011). Thus, the approximate integral that describes the travel time of the ultrasonic pulse in the concrete can be write as

$$T_i = \sum_{j=1}^{n} p_j dL_{i,j} \qquad for\ i = 1, \dots, m \tag{4}$$

where *i* represents each ultrasonic test trajectories. Equation 4 can be represented in matrix form as

$$\boldsymbol{T_m} = \boldsymbol{D_{m,n}} * \boldsymbol{P_n} \qquad (5)$$

where *m* is the total number of pulse readings, *n* is the total number of discretized elements inside the body, *D* is the distance matrix of order *m x n*, *P* is the slowness vector of order *n*, and *T* is the time vector of order *m*.

It is noticed that the time vector is obtained through the readings of the ultrasonic pulse velocity test, and the distance matrix is calculated from the geometric characteristics of the body and the established mesh. Then, the ultrasonic tomographic problem is reduced to determining the vagarosity vector.

2. MATERIALS AND METHODS

2.1 Tomographic tool

The tomographic algorithm used in this work was previously developed by our research group and more details about its implementation can be found in (SACRAMENTO, 2021). For computational development, the described mathematical basis previously shown was used. Fig. 2 illustrates the steps used in the implementation.

The inputs used were the geometric characteristics of the problem to create the distance matrix $D_{m,n}$, and the vector of synthetic time readings T_m. The output is the tomogram that represents the internal section of the simulated object.

Step 1 refers to the data entry of the geometric characteristics of the studied section (height and width). The tomographic process requires the body to be discretized into smaller elements where the numerical operations will be computed. Thus, step 2 of Fig. 2, refers to the mesh definition on the studied element, the positioning of the transducers, and the reading trajectories definition.

The data entry of the time vector T_m is performed in step 3 of Fig. 2. These input data were generated from ultrasonic pulse velocity readings on a concrete specimen.

Once the mesh has been determined, the positions of the transducers, the sections of readings and their lengths, we can proceed to step 4 of Fig. 2, referring to the construction of the distance matrix. In addition to knowing the information about the position of the transducers and the length of the section, it is necessary to compute how much of the reading path goes through each of the discretized elements in the body.

Now that we know the time vector and the distance matrix is calculated, the tomographic system can be set up. Step 5 in Fig. 2 is responsible for this procedure. In step 6 of Fig. 2, the sparsity and condition analysis are performed. In this research we have studied only well-conditioned, and over-determined tomographic problems.

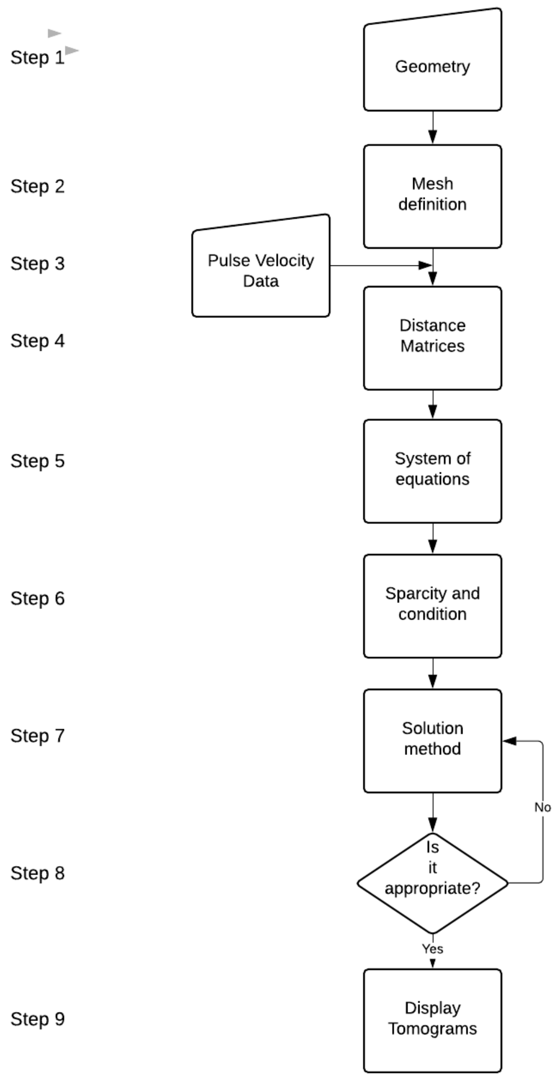

Figure 2. Diagram of the computational implementation process.

Now that we know the components of the system of equations and the characteristics of the distance matrix, we proceed to step 7, the implementation of a solution method. In this stage of the work, the following solution methods will be used: 1- LU factorization with partial pivoting if the distance matrix is square; or QR factorization with column pivoting for other cases.

The obtained result is evaluated in step 8. This step is iterative once, depending on the found results, it is needed to repeat step 7 using a new solution method. Two evaluations must be made to assess the efficiency of the solution method. The first is to verify whether the method can effectively solve the proposed system. The second is related to the methods that effectively manage to solve the system, and consists of verifying if the precision of the obtained result is in agreement with the user's need.

Finally, step 9 in Fig. 2, consists of displaying the vagarosity vector to the user as a tomogram. For that, we use the contour maps representation. Contour maps are already used for the traditional representation of ultrasonic pulse evaluations on concrete (REGINATO *et al.*, 2017b; RIBEIRO *et al.*, 2020). The tomographic reconstruction algorithm was implemented in MatLab.

2.2 Concrete specimens

In order to verify the capacity of the algorithm of developing tomograms, we had chosen the use of concrete specimens with known internal flaws. To simulate the presence of sewer pipes in concrete structures, a 20cm x 20cm x 20cm concrete specimen with a 10cm PVC sewer pipe was developed. Fig. 3 details the developed specimen.

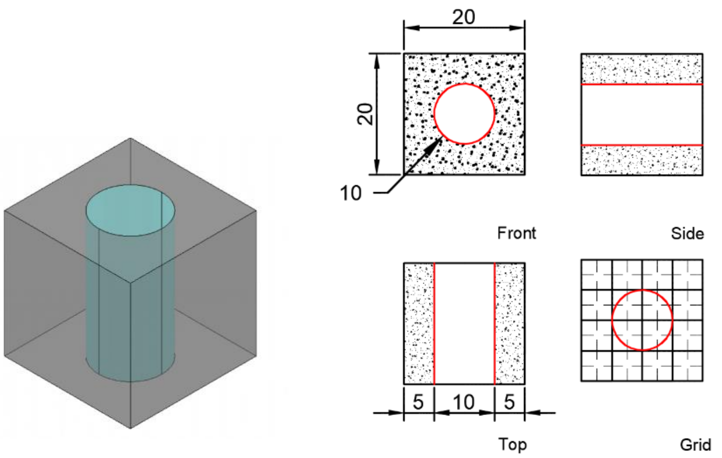

Figure 3. Concrete specimen with a 10cm PVC sewer pipe.

The concrete mix used in this research was developed by LIMA (2020) and is shown in Table 1. This mix proportion was chosen to guarantee a slump between 10 cm and 16 cm. Cement CP V - ARI, river sand from, gravel #1, and water were used.

Concreting took place in layers to ensure homogeneity and better filling of the region around the discontinuity. Thereby, a metal compaction rod was used. A manual vibrator was not used due to the risk of moving the pipe. After 24 hours the mold was removes and the curing process was initiated shortly thereafter. The specimen was kept in a moist cure for 28 days.

Table 1. Mix proportions for reference concrete.

Material	Consume (Kg/m³)
Cement – CP V - ARI	400
Sand	725
Gravel	1056
Water	250

Once the specimen had been cured, the step of regularization and preparation of the reading surface was carried out, and the specimen was sanded with sandpaper #80 and #220. Later, the surface was cleaned with a damp cloth. Fig. 4 illustrates the concreting process, the fresh specimen, the hardened specimen, and the treated surface.

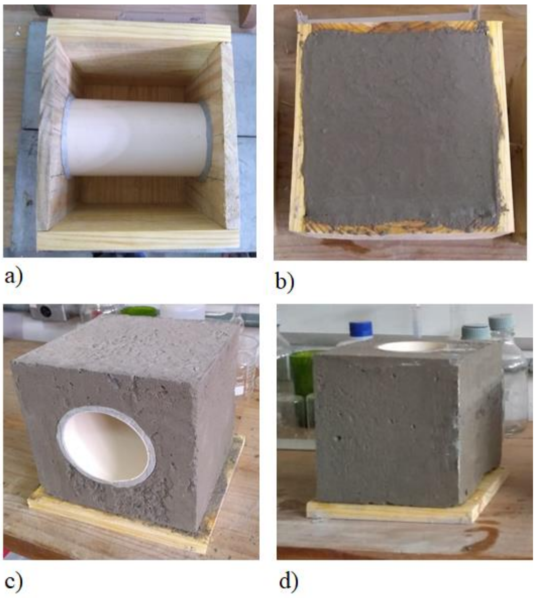

Figure 4. Concrete specimen. a) form for molding the specimen. b) fresh specimen. c) specimen after curing. d) specimen with surface treatment.

2.3 Ultrasonic pulse velocity tests

Once the surface was treated, 5cm x 5cm and 2.5cm x 2.5cm meshes were marked on the specimens. In the dimension perpendicular to the reading mesh, the specimen was divided into 5cm sections identified as sections A, B, C, and D. The intermediate section between B and C was named MID and represents the center of the specimen. Fig. 5 illustrates the specimen with its mesh drawn and sections identified.

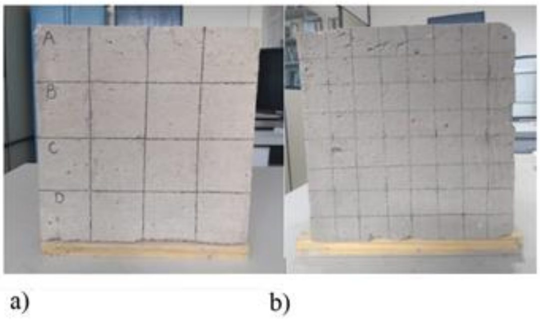

Figure 5. Discretized meshes. a) 5cm x5cm. b) 2.5cm x2.5cm.

In the specimen, three distinct internal sections were analyzed: section A (central plane of the section), section D (central plane of the section), and section MID (central plane of the CP). For each section, both horizontal and vertical readings were performed (Fig. 6). To minimize errors in individual readings, each direction was computed in triplicate, considering the arithmetic mean as the test result. For a 5cm x 5cm mesh, 32 readings per section are required. For a 2.5cm x 2.5cm mesh, 128 readings per section are required. Thus, for 3 sections and performing the readings in triplicate, 1440 ultrasonic pulse velocity readings were performed to carry out the experimental program.

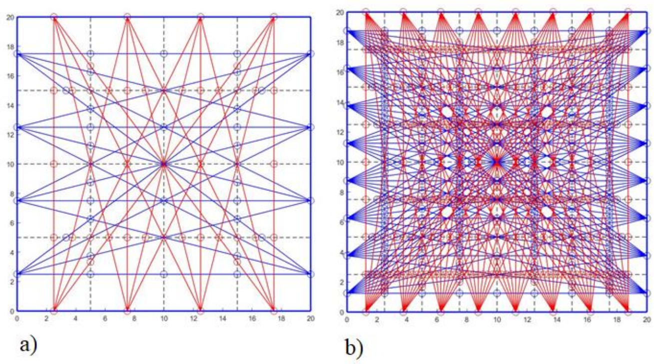

Figure 6. Discretization of readings in each section of the specimen. a) 5cm x5cm mesh. b) 2.5cm x2.5cm mesh.

Ultrasonic pulse propagation tests were performed at LEMER-UESC. Proceq's PunditLab(+) device with 54KHz nominal frequency transducers was used in the tests. Fig. 7 exemplifies the set up of the experiment.

Figure 7. Set up for ultrasonic pulse propagation testing.

The experiment results were used as input data in the developed computational algorithm. The tomograms were generated from the vagarosities obtained from the ultrasonic pulse propagation tests, and from the geometry of the tested specimens. The analysis of the results was then carried out by comparing the tomograms obtained with the geometry, location, and dimensions of the prefixed discontinuities.

3. RESULTS AND DISCUSSION

As described by Perlin (2015), the analysis of the resulting tomograms is a complex process and must be performed by an experienced engineering professional with an understanding of the inhomogeneous properties of concrete, as well as the behavior of wave propagation in inhomogeneous solid media. Fig. 8 shows the resulting tomograms for the concrete specimen with a 10 cm PVC sewage pipe.

In general, when analyzing the tomograms generated from the 5cm x 5cm mesh in Fig. 8, one can see the existence of a discontinuity (represented in blue) inside the specimen. However, its dimensions are not well established. In the tomograms generated from the 2.5cm x 2.5cm reading mesh, the location of the discontinuity in the center of the specimen can also be seen. In this case, there is a better representation of the geometric nature of the section with a shape and size closer to the pipes dimension.

It was noticed that the decrease in the mesh size led to a better quality of the final result, which was expected by the characteristics of the problem. The greater the number of discretized elements, the greater the quality of the generated tomogram. However, it is warned that the gradual decrease of the mesh element must take into account the significant increase in the number of experimental readings, which can make the inspection impossible in practical terms (SACRAMENTO *et al.*, 2021).

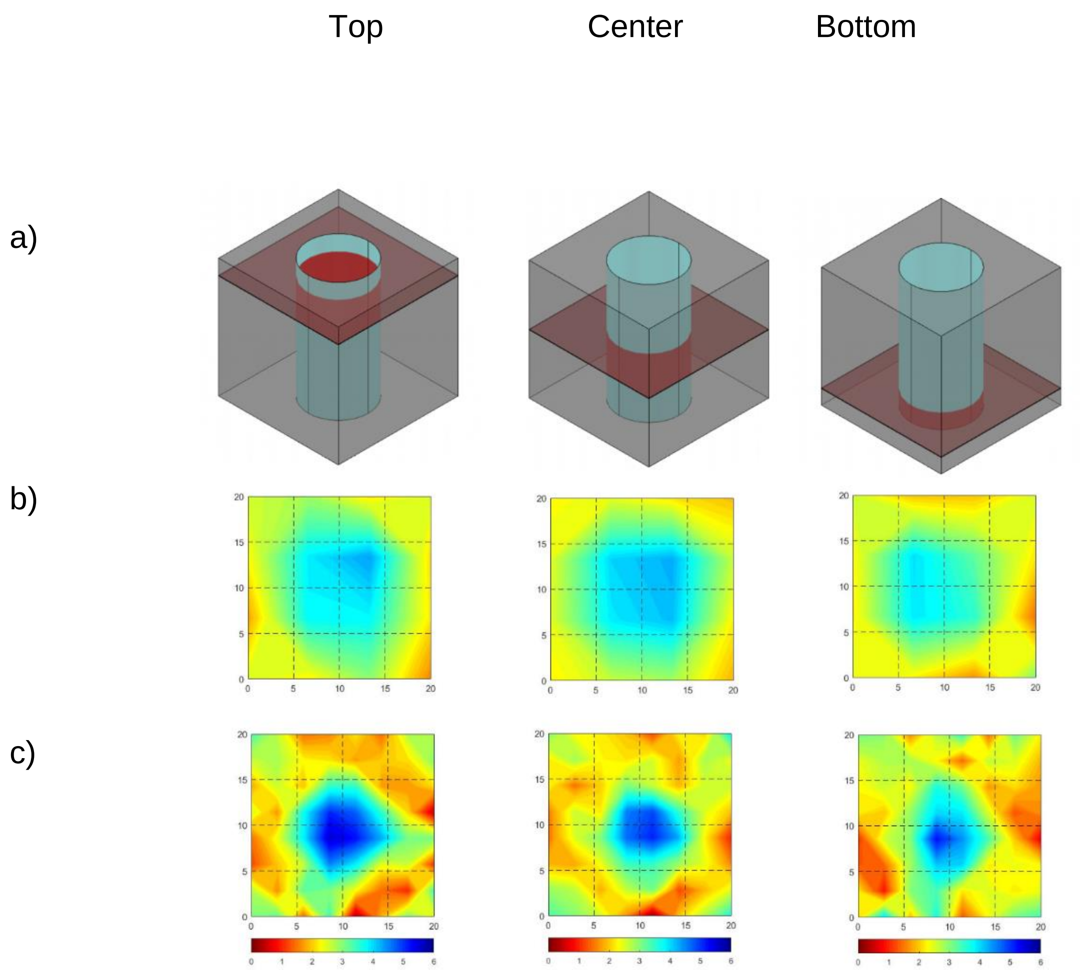

Figure 8. Resulting tomograms for different sections of the concrete specimen with 10cm PVC pipe. a) analyzed section, b) tomogram for a 5cm x 5cm mesh, and c) tomogram for a 2.5 x 2.5cm mesh.

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The color variations of the concrete surface (ranging from yellow to red) found in both tomograms are perfectly acceptable. Such representation is understood to be non-homogeneous regions inherent in the concrete specimen nature.

As described by Sacramento (2021), the quality of ultrasonic pulse velocity readings carried out on concrete bodies is influenced by numerous factors, such as lack of accuracy of the test performer, reading angle, poor coupling of transducers, surface conditions of the tested part, nominal frequency of transducers, among others.

Interferences arising from the conditions of the tested surfaces and the coupling process were reduced by the surface treatment described in section 3.2 and by the use of inert coupling material. Errors arising from the accuracy of the operator were also reduced by running each reading in triplicate. A study on the influence of the nominal frequency of the transducers on the results of the final tomograms was not carried out due to the unavailability of transducers at different frequencies, thus being a suggestion for future work.

Finally, to study the influence of reading angles on ultrasonic velocity results, Emanuelli Junior *et al.* (2010) recommend that a base test for angular correction be performed. For 54 kHz transducers, the authors recommended the creation of a small concrete wall with minimum dimensions of 100 cm x 100 cm x 20 cm. Propagation velocities must be calculated and classified according to their reading angle. The relationship between orthogonal readings and direct readings must be calculated and plotted on a graph. The function that best represents the data should be used as a correction factor for angular dependence. The authors suggest that, in addition to reducing the impact of reading angles, angular correction can improve the results of the final tomograms.

5. CONCLUSIONS

In this work, the use of a computational tool was presented, combining tomographic techniques with the ultrasonic pulse propagation test capable of identifying the presence of PVC sewage pipes in concrete structures.

From the analysis of the generated tomograms, we can conclude that:

- It was possible to present a solution method for sparse, well-conditioned, and over-determined tomographic problems, capable of generating tomograms of the internal structure of the material, and locating the 10cm PVC pipe;
- Mesh dependence has a significant influence on the geometric representation of the internal defect. Smaller meshes lead to better tomograms;
- The color variations of the concrete surface (ranging from yellow to red) found in both tomograms are perfectly acceptable. Such representation is understood to be non-homogeneous regions inherent in the concrete specimen nature;
- Ultrasonic tomography in concrete has great potential to be used to identify non-homogeneities in concrete structures.

The future developments of this research suggest evaluating the ability of the algorithm to generate tomograms from transducers of different nominal frequencies. Evaluating the influence of reading angles on ultrasonic velocities, and developing specimens with different discontinuities to evaluate the generated tomograms.

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