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METHODOLOGY FOR NON-DESTRUCTIVE IDENTIFICATION OF THICKNESS OF UNILATERALLY ACCESSIBLE CONCRETE ELEMENTS BY MEANS OF STATE-OF-THE-ART ACOUSTIC TECHNIQUES

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Abstract. The paper presents a methodology for comprehensive use of ultrasonic tomography and impact-echo – the state-of-the-art acoustic techniques – for non-destructive identification of the thickness of unilaterally accessible concrete elements. Since the techniques are not commonly used, they are little known. Therefore, a brief description of the techniques is given to facilitate the understanding of the subsequently presented methodology. The article gives a practical example of the use of the methodology, which demonstrates its suitability for non-destructive identification of the thickness of concrete elements, particularly those only accessible from one side. In the example, the concrete shell of a heat pipe, carrying tunnel located under a river was tested using the ultrasonic tomography and impact-echo techniques. The tests were carried out according to the proposed methodology. It should be noted that the test results yielded by the two methods were similar. In this way, the proposed methodology has been validated.

Keywords: concrete; ultrasonic tomography; impact-echo; non-destructive identification; ultrasounds.

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Introduction

In building practice, it is often necessary to determine the thickness of a concrete element accessible from one side only. Because of the location of the structure to be tested, it is not always possible to carry out destructive (e.g. drilling) tests. Destructive testing is ineffective when not only the thickness of unilaterally accessible concrete elements, but also the distribution of thickness along the structure or within a larger area of the latter needs to be determined. If such an element (a foundation slab, a wall, a sewer or tunnel shell, etc.) is in contact with, e.g. water, destructive testing is out of question.

In the author's opinion, it is worthwhile to use non-destructive techniques to determine the thickness of unilaterally accessible concrete elements since such non-invasive tests can be carried out in any number of places. The ultrasonic tomography and impact-echo techniques are suitable for this purpose (Gorzelańczyk *et al.* 2012a, b; Gorzelańczyk, Schabowicz 2012; Hoła *et al.* 2008, 2011; Hoła, Schabowicz 2010; Schabowicz, Hoła 2012). Although these acoustic techniques (Hoła, Schabowicz 2010; Gorzelańczyk 2011, 2012; Goszczyńska *et al.* 2012; Hoła, Schabowicz 2010; Stawiski 2012) have been described by Samokrutov and Shevaldykin (2011), Shevaldykin *et al.* (2003) and Sansalone and Strett (1997) and in reports (ACI 228.2R-98 1998; Bundesanstalt für Straßenwesen 2001; ASTM C1383-04 2010), no methodology for their comprehensive (in the sense that the results of tests carried out using one of the techniques are subsequently verified by the results obtained by the other technique) use has been developed. The comprehensive approach is necessary especially when it is impossible to verify the test results in a destructive way. This paper proposes such a methodology and presents its practical verification.

1. Survey of literature

The identification of the thickness of concrete elements, especially the unilaterally accessible ones, has been the subject of studies by Bishko *et al.* (2008), Kozlov *et al.* (1997), Samokrutov *et al.* (2002, 2006), and Samokrutov and Shevaldykin (2011). The researchers proposed to determine the thickness of such elements, using the ultrasonic echo technique. Taffe and Wiggenhauser (2006) proposed to use the impact-echo technique for

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this purpose, and so did Krause *et al*. (2005) and Garbacz and Piotrowski (2010). Bishko (2007) recommends the state-of-the-art ultrasonic tomography technique for determining the thickness of unilaterally accessible concrete elements. Since this technique is new, so far its use has been limited, and very few studies have been undertaken.

The successful application attempts undertaken, by the above researchers, each time involved only one non-destructive testing technique. It is hard to find cases in which two non-destructive techniques, e.g. ultrasonic tomography and the impact-echo technique, were jointly used to identify the thickness of unilaterally accessible concrete elements. Garbacz (2005) and Kurz *et al*. (2012) were the first to use the techniques in a complementary way, employing an automatic multisensor testing system for this purpose. Their studies, however, did not deal directly with the determination of thickness but with the evaluation of the condition of a structure made of reinforced concrete.

On the basis of their own experience (Gorzelańczyk *et al*. 2012a, b; Gorzelańczyk, Schabowicz 2012; Hoła, Schabowicz 2010; Hoła *et al*. 2011 and Schabowicz, Hoła 2012) have come to the conclusion that when jointly used, the non-destructive ultrasonic tomography technique and the impact-echo technique complement each other, and so ensure more effective identification of the thickness of unilaterally accessible concrete elements. It should be noted that in the case of the ultrasonic tomography technique, the measuring place for a single application of the testing antenna covers an area of 100 × 500 mm at a thickness estimation accuracy of a few millimetres. Thus such single measuring places can make up a 500 mm wide and as much as a few metres long measuring band. This means that using this technique one can test large, flat surfaces and identify the thickness of a concrete element within a large area. In the case of the impact-echo technique, the distance between measuring places is no more than 100 mm. For this reason, this technique is labour-intensive when used to test large structures. But it can be complementary to ultrasonic tomography and can be used to verify the latter's results in randomly selected points. The non-destructive testing by these techniques can be easily automated by mounting the testing equipment on a special scanner or robot (Kurz *et al*. 2012).

Taking the above observations (supported by the author's experience in this field) into consideration, this paper presents a methodology for the non-destructive identification of the thickness of unilaterally accessible concrete elements through the comprehensive use of ultrasonic tomography and the impact-echo technique. The methodology is based on the investigations carried out by the author using the two techniques (Gorzelańczyk *et al*. 2012a, b; Gorzelańczyk, Schabowicz 2012; Hoła *et al*. 2008; Hoła, Schabowicz 2010; Schabowicz, Hoła 2012).

Considering that the two techniques are not commonly used for testing, whereby they are less familiar to the readers, they are briefly described below to facilitate the understanding of the proposed methodology. Also an example of the practical use of the methodology is provided.

2. Brief description of used techniques

2.1. Ultrasonic tomography technique

This technique is based on the excitation of an elastic wave in the element being tested. A multi-head antenna (incorporating a few tens of independent ultrasonic heads (probes)) is the exciter. It also receives and processes the ultrasonic signals. The heads generate 50-kHz ultrasonic pulses with a maximum range of 2500 mm.

Figure 1 shows an ultrasonic tomograph which includes a multi-head ultrasonic antenna and a laptop with dedicated software enabling the recording of a graphical image in the form of three mutually perpendicular depictions as illustrated in Figure 1.

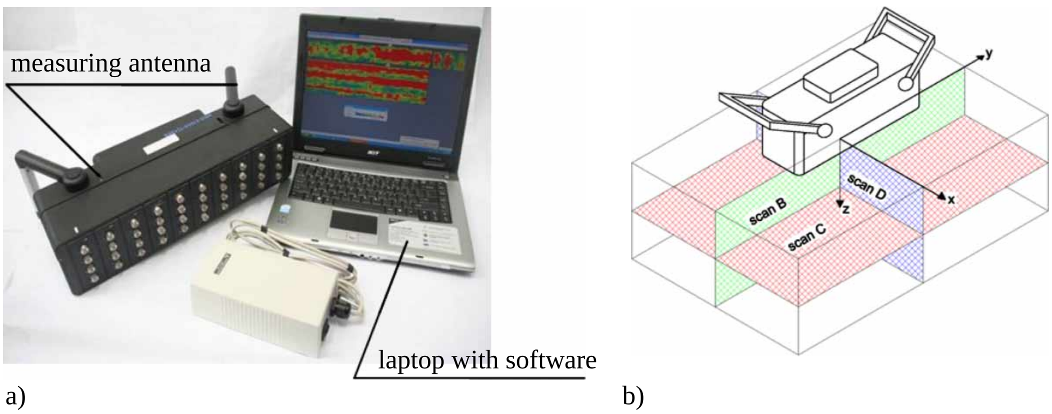


Fig. 1. Ultrasonic tomograph: (a) measuring set; (b) measuring antenna in coordinate system and obtained images

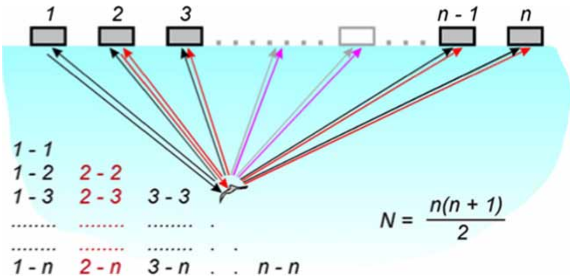


Fig. 2. General schematic of measuring antenna and matrix, illustrating how image is created (Samokrutov *et al.* 2006)

The advantage of this technique is that no means of coupling the surface of the tested element with the ultrasonic heads is required since dry point contact is used. Another advantage is the fast rate of testing whereby large elements, structures and surfaces can be tested in a relatively short time. As for today, the drawback of this technique is difficulties in interpreting the results due to the small experience of the testers and to the requirement that the minimum size (width) of the tested element should be 500 mm.

Figure 2 shows a general schematic of the measuring antenna and the matrix, illustrating how the images are created. The arrows indicate the propagation of ultrasonic signals from their transmission by a head to their reception by the other heads.

The image in each measuring point is displayed as coloured tomogram J (described on the basis of Samokrutov and Shevaldykin (2011)) using Eqn (1):

$$J(x,y) = \frac{1}{N} \cdot \sum_{i=1}^{n} \sum_{j=1}^{n} A\left(Q_i, Q_j\right) \cdot U_{ij}\left(t_0 + \frac{r_i + r_j}{c}\right), \tag{1}$$

where: i, j – the number of antenna table element transmission and reception; $A(Q_i, Q_J)$ – a weight index based on the directions in the table element transmission and reception diagrams; $U_{ij}(t)$ – the signal from i (antenna matrix element transmission) and j (antenna matrix element reception); t_0 – the hardware delay; r_i, r_j – the distance from the point of sharpness to the transmission and reception of the antenna table elements; c – the ultrasonic speed in the material being tested.

2.2. Impact-echo technique

The measuring set used in the non-destructive impact-echo technique is shown in Figure 3. It is comprised of measuring heads with exciters in the form of a set of steel balls with different diameters and a laptop. This technique consists in exciting an elastic wave in the tested element by striking its surface with the exciter. The frequency of the generated vibrations ranges from 10 to 150 kHz. The dedicated software enables the recording of the graphical image of the elastic wave propagating in the tested element, in the amplitude-time system and the conversion of this image into an amplitude-frequency spectrum by means of the fast Fourier transform or artificial neural networks (Hoła, Schabowicz 2010). The spectrum is subjected to further analysis.

According to Gorzelańczyk *et al.* (2012a, b), this technique exploits the dependence between frequency f_T, elastic wave velocity in concrete C_p and the depth at which a defect occurs or element thickness T, as shown in Eqn (2):

In the obtained amplitude-frequency spectrum, one can distinguish dominant frequency f_{T1} corresponding to element thickness. If no defect occurs in the tested element, its thickness T_1 can be determined on the basis of the amplitude-frequency spectrum and by substituting Eqn (2) into Eqn (3):

$$f_T = \frac{0.96 C_p}{2 f_{T1}}; \tag{2}$$

$$T_1 = \frac{0.96 \cdot C_p}{2 \cdot f_{T1}}. \tag{3}$$

If the surface layer and the base layer are made of different materials with respective thicknesses T_3 and T_4, whereby the elastic wave velocity C_{p3} in the surface

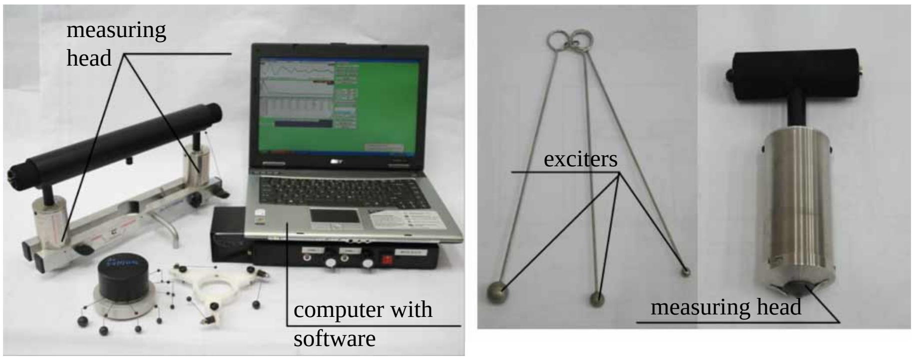


Fig. 3. Idea of impact-echo technique: (a) measuring set; (b) exciters and measuring head

layer is different from elastic wave velocity C_{p4} in the base layer, Eqn (2) assumes this form:

$$f_{T3} = \frac{1}{\frac{2 \cdot T_3}{0.96 \cdot C_{p3}} + \frac{2 \cdot T_4}{0.96 \cdot C_{p4}}}. \quad (4)$$

3. Methodology for non-destructive identification of thickness of unilaterally accessible concrete elements

The proposed methodology for the non-destructive identification of the thickness of unilaterally accessible concrete elements, using the non-destructive acoustic techniques of ultrasonic tomography and impact-echo in a comprehensive way, is shown graphically in Figures 4 and 5 and described below. Figure 4 presents a general diagram of the methodology, while Figure 5 shows a detailed diagram of the methodology.

It is proposed to carry out the non-destructive identification of the thickness of a unilaterally accessible element in two stages, using the two non-destructive techniques.

In stage 1, tests using the ultrasonic tomography technique should be carried out.

First, i measuring places are selected, and measuring bands are marked. At least one measuring band, with a minimum width equal to the width of the measuring antenna (depending on the type of antenna the width amounts to 380 or 500 mm), should be marked in one measuring place. The length of the band may reach a few metres (depending on the memory capacity of the data carrier). The measuring band is made up of n measuring points spaced at every 100 mm. Then the instrument is calibrated by

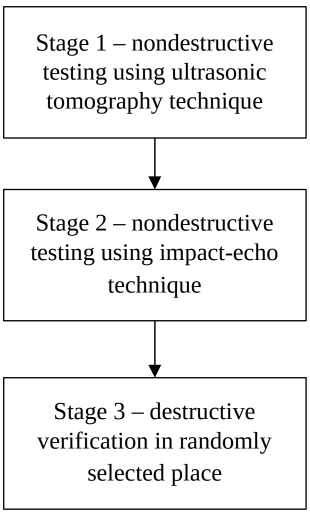


Fig. 4. General diagram illustrating methodology for non-destructive identification of thickness of unilaterally accessible concrete element by means of acoustic ultrasonic tomography and impact-echo techniques

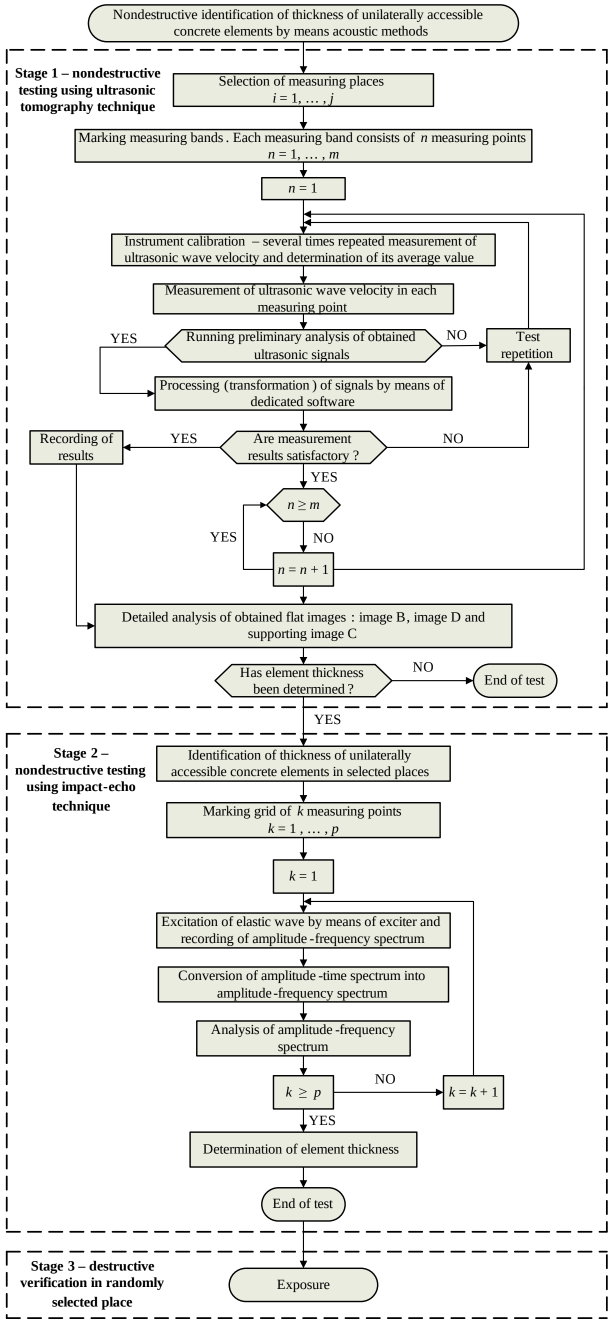


Fig. 5. Detailed diagram illustrating methodology for non-destructive identification of thickness of unilaterally accessible elements by means of acoustic ultrasonic tomography and impact-echo techniques

measuring the ultrasonic wave (signal) velocity in the tested element, and its average value is determined.

Subsequently, the ultrasonic wave velocity should be measured in each of the measuring points. The measurements can be automated by mounting the testing equipment on a special scanner or robot. During each measurement, a preliminary analysis of the ultrasonic signals, consisting in checking whether the element thickness in given measuring point can be determined from the particular measurement is carried out. If this is not the case, the test should be repeated. Otherwise, the signals should be processed (transformed) using the dedicated software. The processing consists of assembling the data acquired from the particular measuring points in the given measuring band. If the measurement results are not satisfactory, the test should be repeated. If the measurement results are satisfactory, they should be recorded. As a result, flat images (B, C and D) of the inside of the tested concrete element in three mutually perpendicular directions are obtained, as illustrated in Figure 1. The thickness of the tested concrete element is identified through a detailed analysis of the images, especially images D and B. Image C performs a support function, enabling one to correct the results obtained on the basis of images D and B, by comparing images C at every millimetre – a few millimetres in the boundary zone of the identified element thickness.

In stage 2, the thickness identified by means of the ultrasonic tomograph is verified to validate the test results obtained in stage 1. The verification should be done using the impact-echo technique.

First, a grid of k measuring points should be marked in randomly selected measuring places in the measuring bands tested in stage 1. It is recommended that the measuring points should be spaced at no more than every 100 mm (Hoła *et al*. 2011). Then an elastic wave is generated in each of the points by means of the exciter, and the amplitude-time spectrum is recorded (Hoła *et al*. 2011). Subsequently, the spectrum is converted into an amplitude-frequency spectrum by means of the dedicated software using a fast Fourier transform algorithm (Hoła *et al*. 2011). Then the amplitude-frequency spectrum for each of the measuring points should be analysed to determine the thickness of the tested concrete element.

If possible, in stage 3, the non-destructively identified thickness of the tested element should be verified in a destructive way (through an exposure in a randomly selected place(s)).

4. Example of practical use of the methodology to test unilaterally accessible concrete shell of heat pipe carrying tunnel

A heat pipe carrying tunnel under one of the largest rivers in Poland, located at a depth of 10–20 m below the water level, was tested. This more than 900-m-long

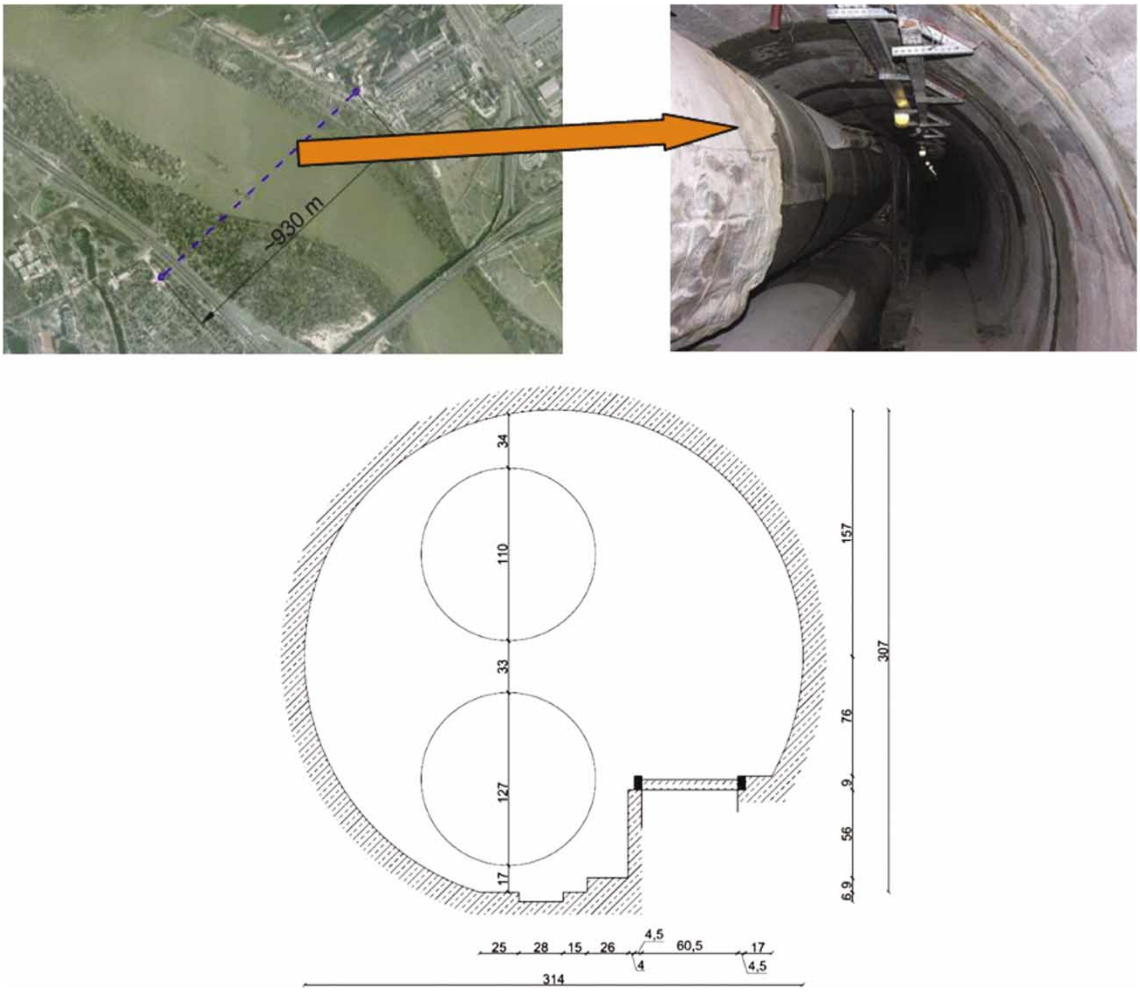


Fig. 6. Location, general view and cross section of tested tunnel under river (Gorzelańczyk *et al*. 2012b)

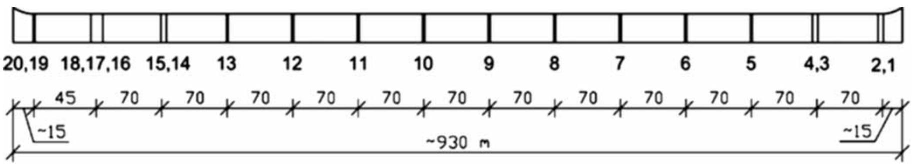
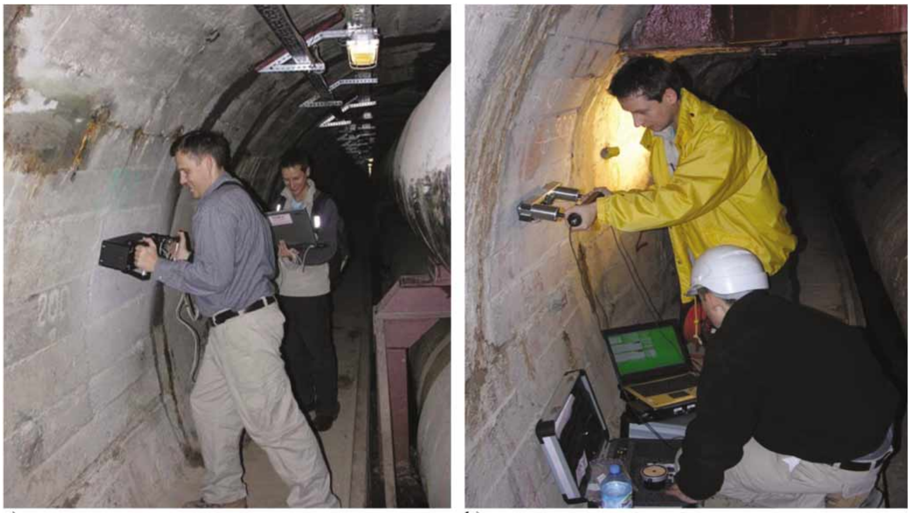


Fig. 7. Measuring places in tested tunnel



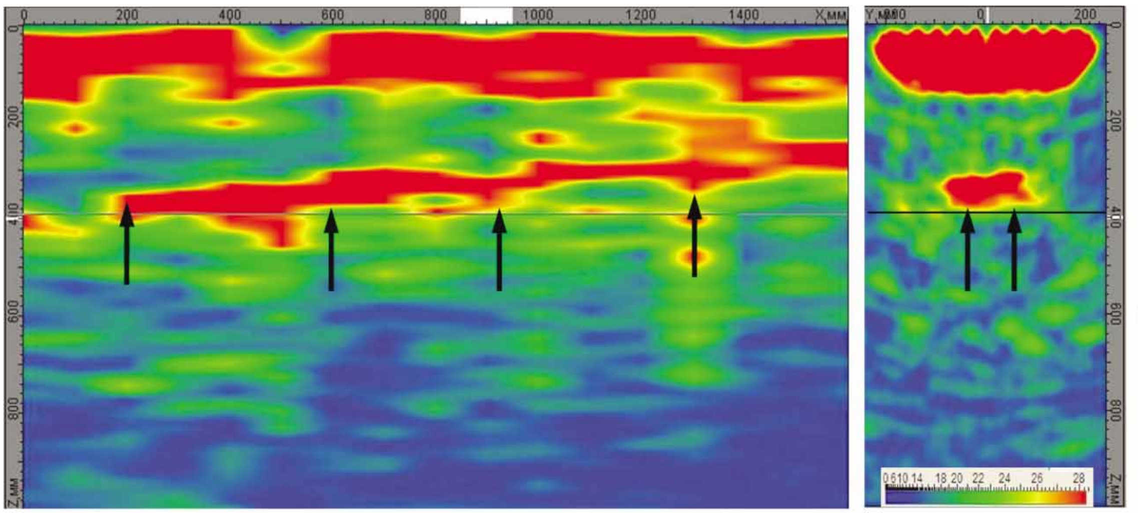
a) b)

Fig. 8. Testing by: (a) ultrasonic tomography technique; (b) impact-echo technique

structure with an inside diameter of about 3.5 m was built (manually bored) in the 1950s. The tunnel shell was made of concrete. Figure 6 shows the location of the tunnel and its general view. Today, the tunnel holds two pipes (each 900 mm in cross section) carrying hot water from a heat and power plant to households and a service walkway.

In connection with the planned renewal of the tunnel, the load-bearing capacity of the tunnel's concrete shell had to be determined. Since no tunnel design documents have survived, it was necessary to determine the thickness of the unilaterally accessible tunnel shell and the variation of this thickness along the tunnel length. Because of the tunnel location, no destructive tests (drilling through the tunnel shell) could be carried out. Therefore, it was decided to investigate the tunnel, using the non-destructive ultrasonic tomography and impact-echo techniques.

First, using an ultrasonic tomograph, the tunnel shell was tested in 20 randomly selected places, as



a) b)

Fig. 9. Exemplary results obtained in measuring place no. 1: (a) image D; (b) image B

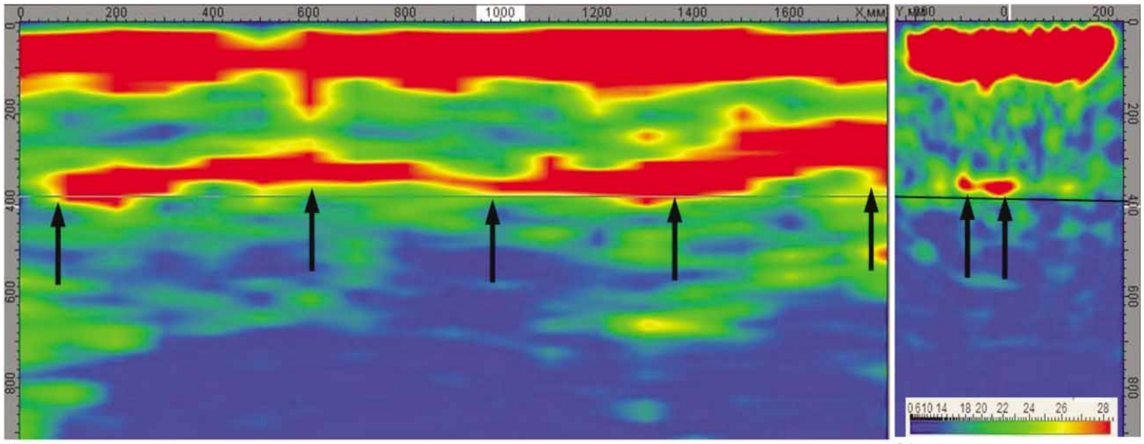


Fig. 10. Exemplary results obtained in measuring place no. 7: (a) image D; (b) image B

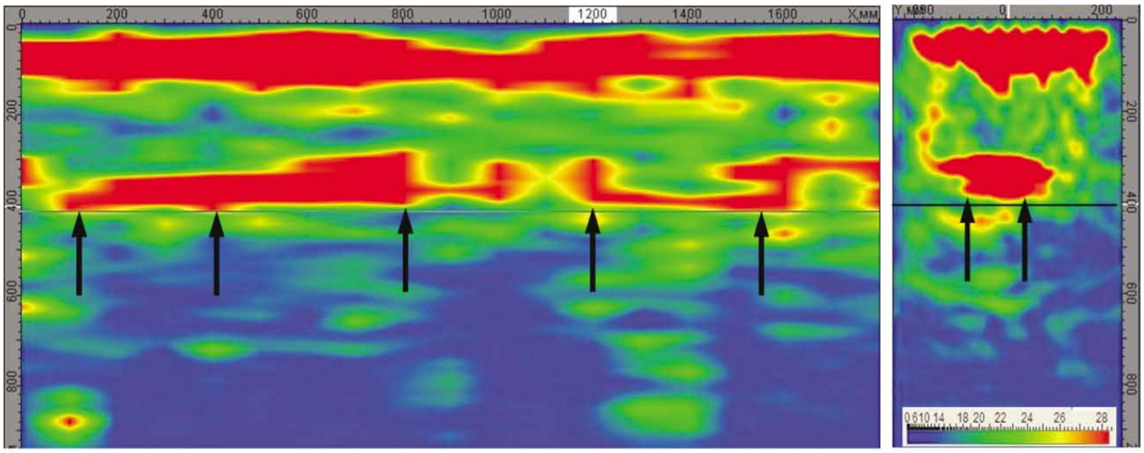


Fig. 11. Exemplary results obtained in measuring place no. 19: (a) image D; (b) image B

shown in Figure 7. In each of the measuring places, tests were carried out in 500-mm-wide and 1500-mm-long measuring bands. The tests were carried out according to the proposed methodology described in Section 4, as shown in Figure 8. Altogether there were about 400 measuring points. In each of the measuring points, the ultrasonic wave velocity was measured and a preliminary analysis of the ultrasonic signals was made. After the signals were processed, the results were recorded, and the obtained images were analysed in detail to determine the thickness of the unilaterally accessible shell of the heat pipe carrying tunnel.

The images of the cross sections in each of the measuring antenna positions were collected in a three-dimensional matrix table, and the three mutually

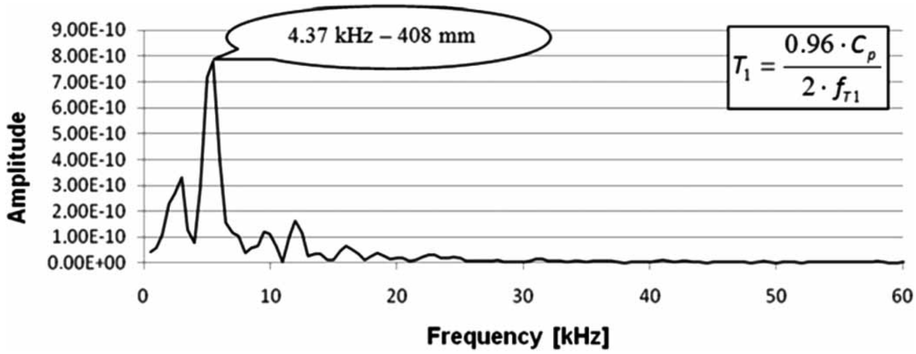


Fig. 12. Amplitude-frequency spectrum recorded in measuring place 7, using impact-echo technique

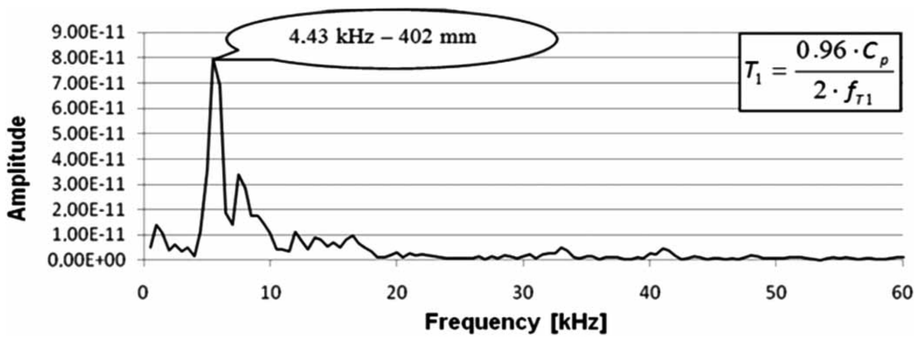


Fig. 13. Amplitude-frequency spectrum recorded in measuring place 11, using impact-echo technique

intersecting cross sections (images B, C and D) of the examined object were obtained on this basis. Figures 9–11 show exemplary images B and D obtained in measuring places, numbers 1, 7 and 19. The shell thickness is marked with a solid line and, additionally, with arrows. In the bottom right corner in Figures 9b–11b, there is a scale of correspondence between the ultrasonic dispersion level in a point of the tested concrete tunnel shell and the colour representing it. The ultrasonic dispersion level indicates changes in the physical characteristics which are different from those of the concrete in this area. Also which may be indicative within the examined band, of a material which density is different than that one of the concrete.

In the second stage of testing, the impact-echo technique (Fig. 8b) was used to verify the determined thickness and validate the test results obtained from the ultrasonic tomograph. For this purpose, three measuring points were randomly selected in each of the measuring places marked in stage 1. Altogether there were about 60 measuring points. An elastic wave was excited in each of the measuring points and the amplitude-time spectra were recorded. The latter were converted into amplitude-frequency spectra and analysed.

Figures 12 and 13 show exemplary test results in the form elastic wave amplitude-frequency spectra recorded in measuring places, numbers 7 and 11 using the impact-echo technique.

The test results obtained using the ultrasonic tomography and impact-echo techniques showed the thickness of the concrete tunnel shell was not uniform, ranging from 389 to 416 mm, as shown in Figure 14.

In order to verify the obtained results, a destructive test consisting of drilling through the shell in a randomly selected place was carried out. It was found that the concrete tunnel shell was 400 mm thick.

Conclusions

A methodology for the non-destructive identification of the thickness of unilaterally accessible concrete elements by means of the state-of-the-art acoustic

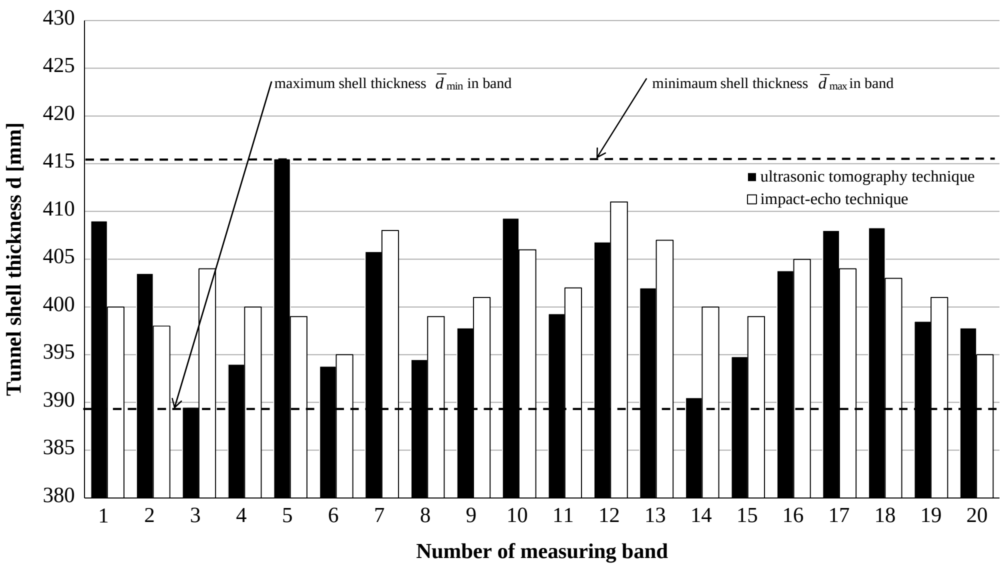


Fig. 14. Thickness of the concrete tunnel shell in particular measuring places, determined using ultrasonic tomography and impact-echo techniques

techniques of ultrasonic tomography and impact-echo used in a comprehensive way has been presented. Since the techniques are not commonly used, they are little known. Therefore, in order to facilitate the understanding of the methodology, the presentation of the latter was preceded by a brief description of the techniques.

Two main stages in testing according to the proposed methodology are distinguished: stage 1, in which, non-destructive tests are carried out, using the ultrasonic tomography technique and stage 2, in which, non-destructive tests are carried out, using the impact-echo technique. This can be followed by a stage in which the test results are verified by means of an exposure. Stage 3 is not always possible. If the area or length of the element to be tested is large, the non-destructive tests can be automated by mounting the testing equipment on a special scanner or robot.

An example of the practical use of the methodology, demonstrating its suitability for the non-destructive identification of the thickness of concrete elements, particularly the ones accessible from one side only, was provided. In the example, the concrete shell of a heat pipe carrying tunnel located under a river was tested using the ultrasonic tomography and impact-echo techniques. The tests were carried out according to the proposed methodology. An analysis of the test results showed that the thickness of the concrete tunnel shell was not uniform along its length, ranging from 389 to 416 mm. It should be noted that the test results yielded by the two methods were similar. In this way, the proposed methodology has been validated.

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