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METHODOLOGY OF NONDESTRUCTIVE IDENTIFICATION OF DEFECTIVE CONCRETE ZONES IN UNILATERALLY ACCESSIBLE MASSIVE MEMBERS

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Abstract. The paper deals with the nondestructive identification of defective concrete zones in unilaterally accessible massive members, for example, access galleries in hydroelectric power plants. The concrete in such zones is, for various reasons, excessively porous. The authors propose to use state-of-the-art acoustic testing techniques, including ultrasonic tomography, integratively to detect and identify defective zones. An original methodology for such tests has been developed. The methodology is illustrated with an example of its practical application to a real civil engineering structure.

Keywords: concrete, durability, water pressure, vibrations, honeycombing, acoustic techniques, nondestructive tests, impulse response, ultrasonic tomography.

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Introduction

The massive members of hydroelectric power plants, dams, and other structures are erected from concrete – one of the principal construction materials (Kmiecik, Kamiński 2011; Soutsos *et al.* 2011; Angst *et al.* 2012; Musiał 2012). Because of the great thickness and mass of the concrete such structures incorporate they are prone to locally develop defective zones during construction. These are zones in which the concrete mixture was not vibrated. There are also zones in which the concrete mixture contained large aggregate particles, which were not sufficiently enveloped with cement mortar. In such zones, the hardened concrete is excessively porous (honeycombed). The zones are macrononhomogeneities which in extreme cases can locally occupy a volume of up to several cubic meters.

In the course of their service, such structural members are usually simultaneously subjected to unilateral water pressure and vibrations. This applies, for example to the walls of access galleries in hydroelectric power plants. As a result of the continuous vibrations generated by the operating power plant turbines, with time zones of excessively porous state, and so weaker, concrete can interconnect via cracks propagating in the concrete, whereby "paths" pervious to water form across the wall. Water flowing along the "paths" increases the leakiness of the walls. Water dissolves and washes out calcium hydroxide ($Ca(OH)_2$) from the hardened cement grout. As lime is being leached, leakiness increases further and the compression strength of the concrete decreases. This adversely affects the durability of the concrete members (Safinowski 2011; Łowińska-Kluge, Błaszczyński 2012; Łydżba *et al.* 2012).

Water leakages into the gallery make its use difficult. Attempts at sealing the leaking places without a prior reconnaissance aimed at locating the zones of weaker concrete and determining their extent are ineffective at long term, since new leaking places (indicating that new paths of water leakage through the wall have formed) appear besides the already sealed places, as shown in Figure 1. In order to effectively solve the troublesome problem of water leaks it is necessary to detect and locate, adequately early, the defective zones in the unilaterally accessible massive concrete member, at least to a depth of about 1000–1500 mm.

The detection and location of such zones of defective (excessively porous) concrete in members

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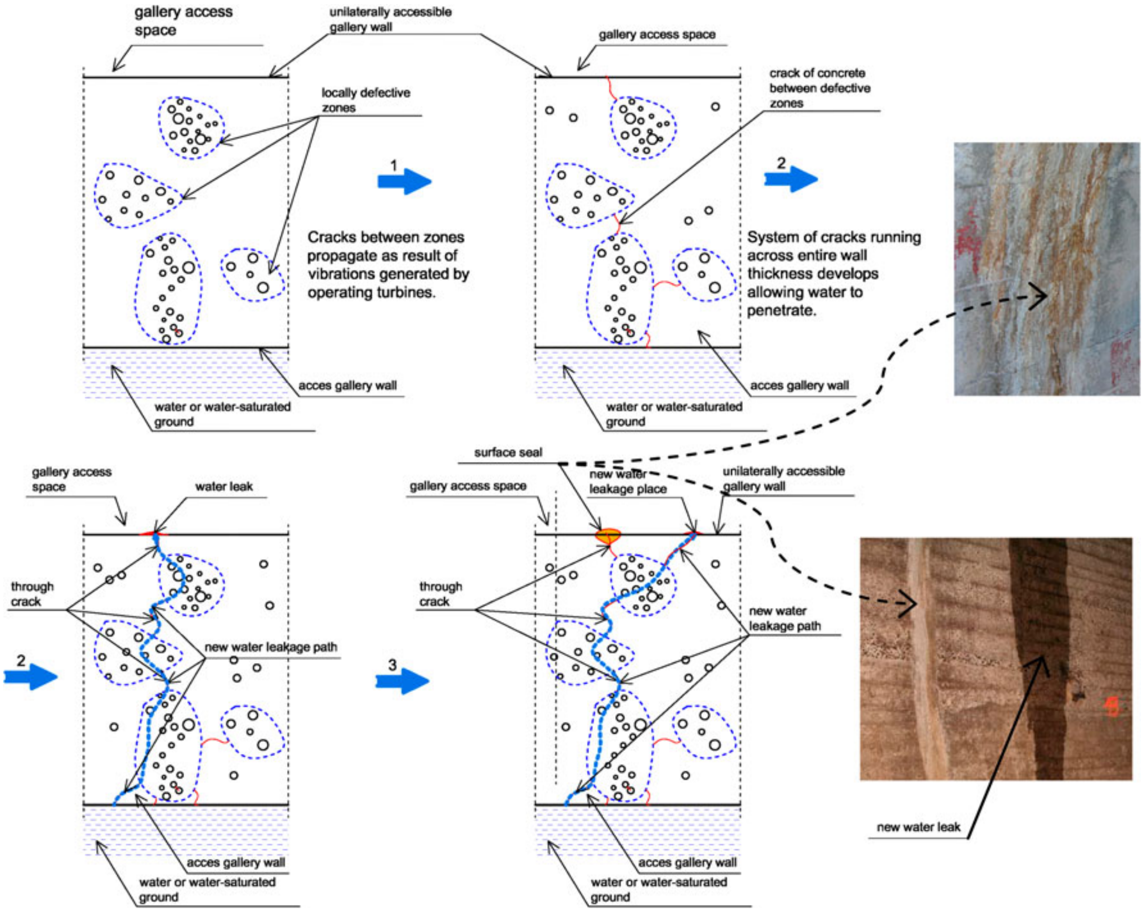


Fig. 1. Hydroelectric power plant access gallery and illustration of how water leaks through its walls arise

accessible from only one side is not easy. Nondestructive acoustic techniques, especially the state-of-the-art impulse response technique (ASTM C1740-10 2010) and ultrasonic tomography (Hoła, Schabowicz 2010; Schabowicz, Hoła 2012), increasingly and often used today to diagnose building structures, can be helpful in this regard (Schickert 2005; Beutel *et al.* 2008; Maksymowicz *et al.* 2011; Zwolski, Bień 2011; Goszczyńska *et al.* 2012; Leibbrandt *et al.* 2012; Ožbolt *et al.* 2012).

In this paper the authors propose, on the basis of their research experience to date (Schabowicz *et al.* 2010; Gorzelańczyk *et al.* 2012a, b; Schabowicz, Hoła 2012), an original test methodology, integrating the latest nondestructive techniques, for identifying and locating defective zones in unilaterally accessible massive concrete members. The methodology has already been used in practice. An example of its use is provided.

Since the two nondestructive diagnostic techniques have not been commonly used so far, and hence are less known, a concise description of them, necessary to understand the proposed methodology is included.

1. Survey of literature

The identification of defects, including excessively porous zones, in unilaterally accessible concrete members by means of ultrasonic tomography, has been studied, among others by Bishko *et al.* (2008), Kozlov *et al.* (1997), Samokrutov *et al.* (2002, 2006), Samokrutov, Shevaldykin (2011) and Shevaldykin *et al.* (2003). Also in Bishko (2007) the nondestructive ultrasonic tomography method was recommended for identifying defects in concrete members. Stawiski (2012) used the nondestructive ultrasonic method and point probes to identify concrete nonhomogeneities in horizontally formed members. Quiviger *et al.* (2010) proposed to use the nondestructive ultrasonic echo method to identify macrononhomogeneities and macrocracks in concrete members. In Garbacz and Piotrowski (2010), Krause *et al.* (2005) and Taffe, Wiggenhauser (2006) it is proposed to use the impact-echo method for this purpose. In Davis (2003), Davis *et al.* (1996) Hertlein, Davis (1998) and Ottosen *et al.* (2004) the nondestructive impulse response method is recommended for locating defects in concrete members. The above authors studied relatively thin concrete members, each time using a single nondestructive method.

In the literature, one cannot find any study dealing with the identification and location of defects in the form of excessively porous concrete in unilaterally accessible massive concrete members, for which purpose, at least two of the above nondestructive acoustic methods, for example, the impulse response method and the ultrasonic tomography method, would be used sim ultaneously. Although the authors Kurz *et al.* (2012) and Huston *et al.* (2011) came up with an idea of the integrated use of the methods, the experiments they conducted were not directly connected with the location of zones of excessively porous concrete.

The present authors' research indicates that the nondestructive acoustic methods of impulse response and ultrasonic tomography when used integratively, complement each other. Owing to this they can be useful in identifying and locating defective zones (concrete macrononhomogeneities) in massive members accessible from only one side. The impulse response method is suitable for the fast searching of defects in large concrete surfaces and enables one to approximately identify and locate such defects in up to 1500 mm thick members, but the depth at which a defect occurs cannot be directly assessed. This possibility is offered by ultrasonic tomography, enabling one to identify and spatially locate defects in massive members with a thickness of up to 2500 mm.

2. Concise description of nondestructive methods integrated in proposed methodology

Table 1 presents basic information on the impulse response method, including: a brief description, a schematic of the test setup, the registered parameters, and sample tests results. A more comprehensive description of this test method can be found in Hoła, Schabowicz (2010) and Hoła *et al.* (2011).

Table 2 presents basic information on the ultrasonic tomography method. A more comprehensive description of this method can be found in Hoła, Schabowicz (2010) and Schabowicz, Hoła (2012).

3. Proposed methodology of nondestructive tests

The methodology proposed for the nondestructive identification and location of defective (macrononhomogeneities) concrete zones in unilaterally accessible massive members through the integrated use of state-of-the-art acoustic methods of impulse response and ultrasonic tomography is graphically presented in Figures 2 and 3 and described below.

As Figure 3 shows, it is proposed to carry out the investigations in two stages.

In stage I, the impulse response method is used to identify and superficially locate defective concrete zones present in the tested member.

For this purpose i measuring places should be marked on the tested concrete member. In each of the places one should mark a grid of n measuring points spaced at every 1000 mm, keeping a minimum distance of 500 mm from the edge of the tested member. If the surface area of the latter is very large one can increase the spacing to 2000 mm. The maximum testing range, that is the distance from the surface, amounts to about 1500 mm.

Then an elastic wave is generated by striking with the calibrated hammer in each point of the marked measuring grid, and after each strike the value of elastic force F generated by the hammer, the diagram of elastic wave velocity w and the diagram of mobility N are analyzed. The conditions, the satisfaction of which guarantees satisfactory reliability of the obtained results are specified in ASTM C174010 (2010), Hoła *et al.* (2011) and Hertlein, Davis (1998).

If the results are found to be satisfactory, they should be processed using the dedicated software. In this way the values of the characteristic parameters, that is average mobility N_{av}, stiffness K_d, mobility slope M_p, mobility times mobility slope $N_{av} \cdot M_p$, and voids index w, in each of the measuring grid points are obtained. Then maps showing the distribution of the parameter values on the surface of the tested member should be plotted.

The final step in this stage is a detailed analysis of the maps, the aim of which is to approximately identify the zones where it is highly probable that defects occur.

Then one should move to stage II of the investigations, using the ultrasonic tomography method to confirm the defects detected by the impulse response method and to locate them along the depth of the tested member.

First, k measuring bands should be marked in the zones found to be defective. At least one measuring band with a minimal width equal to that of the measuring antenna and having the desired length should be marked in each such zone. Depending on the type of the antenna, the band is 380 or 500 mm wide while its length may amount to several meters.

Then one should calibrate the tomograph by measuring the velocity of the ultrasonic wave (signal) in a given zone several times and determining its average value.

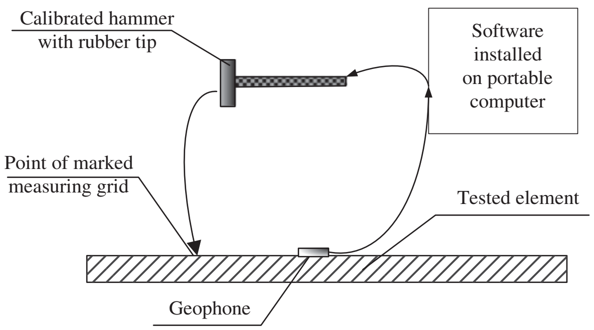
Subsequently, one should measure the velocity of this wave in each antenna application place in each of the bands. In the course of the measurement the ultrasonic signals should be preliminarily analyzed to determine whether the defect can be identified on their basis. If this is not the case, the test should be repeated. If the answer is yes, the signals should be

Table 1. Concise description of impulse response method (Davis *et al.* 1996; Hertlein, Davis 1998; Davis 2003; Ottosen *et al.* 2004)

Description of method

The impulse response method consists in exciting an elastic ultrasonic wave in the tested member by means of a calibrated hammer with a rubber tip. The frequency of the excited wave is in a range of 1–800 Hz, while the range of excitation around the test point amounts to 1000 mm. The method is suitable for the approximate location of areas in which defective zones in the form of concrete nonhomogeneities may occur in unilaterally accessible members, to a depth of about 1500 mm.

Schematic of test setup



Test procedure

Calibrated hammer strikes are delivered in selected test points of a grid of, for example, 1000 × 1000 mm, squares marked on the surface of the tested member. The signal of the elastic wave propagating in the member is registered by a geophone and amplified. The signals recorded in the course of the test are processed using dedicated software installed on a portable computer. In this way the values of five parameters are obtained.

Registered parameters

In each test point the values of the following parameters are registered:

- average mobility N_{av};
- stiffness K_d;
- mobility slope M_p/N;
- mobility times mobility slope $N_{av} \cdot M_p/N$;
- voids index *v*.

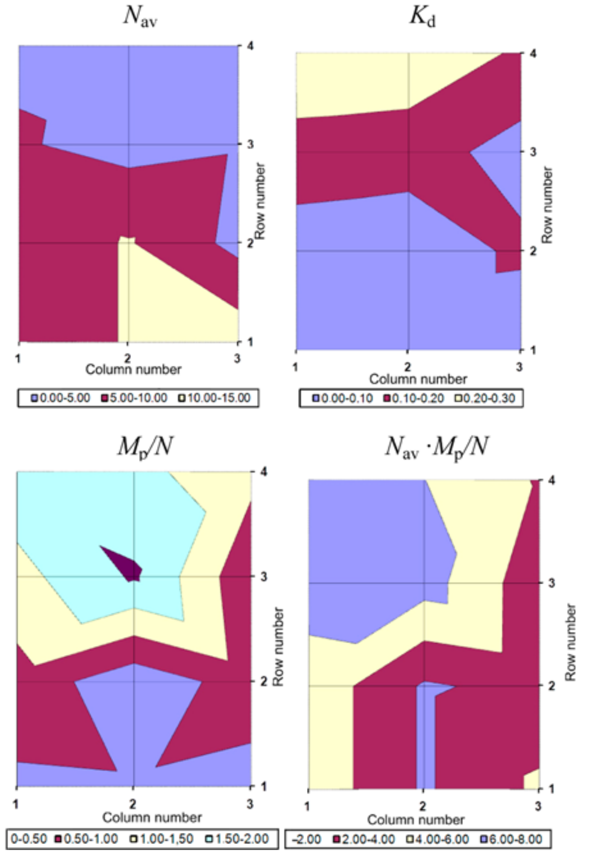
Maps showing the distribution of the above parameters on the surface of the tested member are plotted on this basis.

Sample results and their analysis

Typical maps showing the distribution of the registered parameters on the surface of the tested member are presented as follows:

Table 1. (*Continued*)

Sample results and their analysis



An analysis of the parameter values is carried out, considering that, for example,

– a local increase in the value of parameter N_{av} in a given test point may indicate a smaller thickness of the member in this point or a nonhomogeneity in the concrete;
– a local decrease in the value of K_d in a test point may indicate a nonhomogeneity in the concrete there, a delamination of layers, and so on;
– a high value of parameter M_p/N is closely connected with the presence of defects, for example, delaminations in the cross section of the tested member or an inadequate interlayer bond;
– if parameter $N_{av} \cdot M_p/N$ reaches a value higher than $3\ 10^{-7}$ m/s·N this means that a defective area occurs in the tested place;
– if the value of coefficient *v* is higher than 2, this may indicate a defective area.

processed using the dedicated software. The processing consists in assembling the data recorded for a given measuring band.

If the results are satisfactory, they are recorded and flat images B–D, showing the inside of the concrete member in the given zone, in three mutually perpendicular directions are obtained. The defective

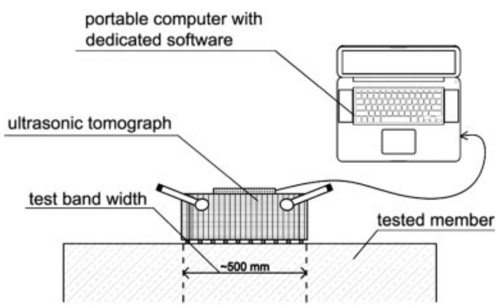
Table 2. Concise description of ultrasonic tomography method (Kozlov *et al.* 1997; Bishko 2007; Bishko *et al.* 2008)

Description of method

The ultrasonic tomography method consists in exciting an elastic wave in the tested member. The exciter is a multihead antenna (incorporating tens of integrated ultrasonic heads) which is also used to receive and process ultrasonic signals. The heads generate ultrasonic pulses with a frequency of 50 kHz. The maximum test range amounts to 2500 mm of the tested member thickness.

The tomograph has been designed to determine the thickness of unilaterally accessible concrete member and to detect cracks, inclusions, air voids, and other places which may be empty or filled with a liquid or a material differing in its density and other physical mechanical properties from the surrounding concrete.

Schematic of test setup



Test procedure

In the course of the test the ultrasonic tomograph antenna is moved stepwise (at a step of 100 mm) in the same direction in a given 380 mm or 500 mm wide (depending on the antenna type) test band. The obtained results, in the form of images of the cross sections in each antenna position, are collected in a three-dimensional matrix table. Using this matrix table and the dedicated software installed on a portable computer one obtains three images B–D in three mutually perpendicular directions, as shown in the following figure:

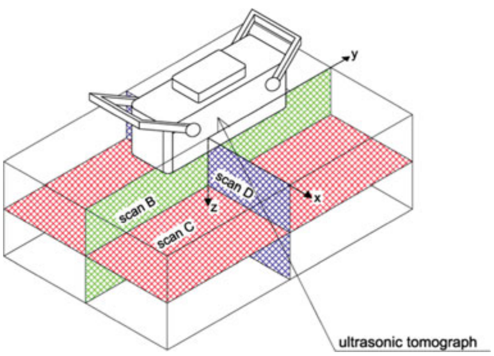
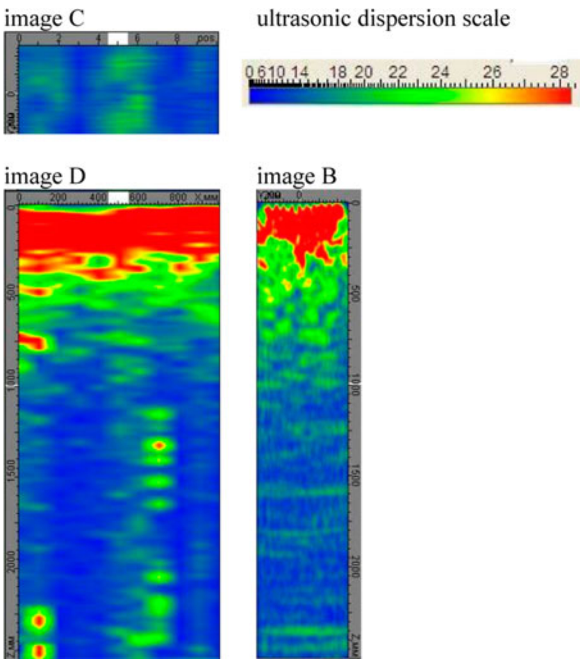


Table 2. (*Continued*)

Results and their interpretation

Using this method one obtains three mutually perpendicular images B–D in each of the 380 or 500 mm wide test band and an ultrasonic dispersion level color scale assigned to the images, as shown in the following figure:



The interpretation of the obtained results comes down to the analysis of the images. From the differences in the level of ultrasonic dispersion one can infer whether the physical characteristics of the media differ or do not differ from each other in the tested area, which means that one can infer whether within the tested band there is a material (air voids, concrete zones of different density, large inclusions, etc.) whose density is different than that of the concrete.

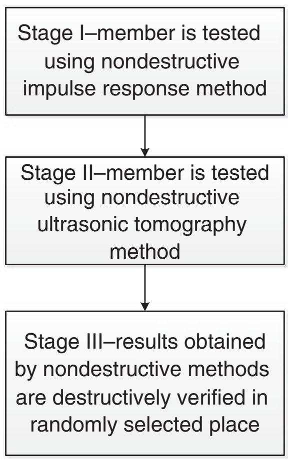


Fig. 2. Hydroelectric power plant access gallery and illustration of how water leaks through its walls arise

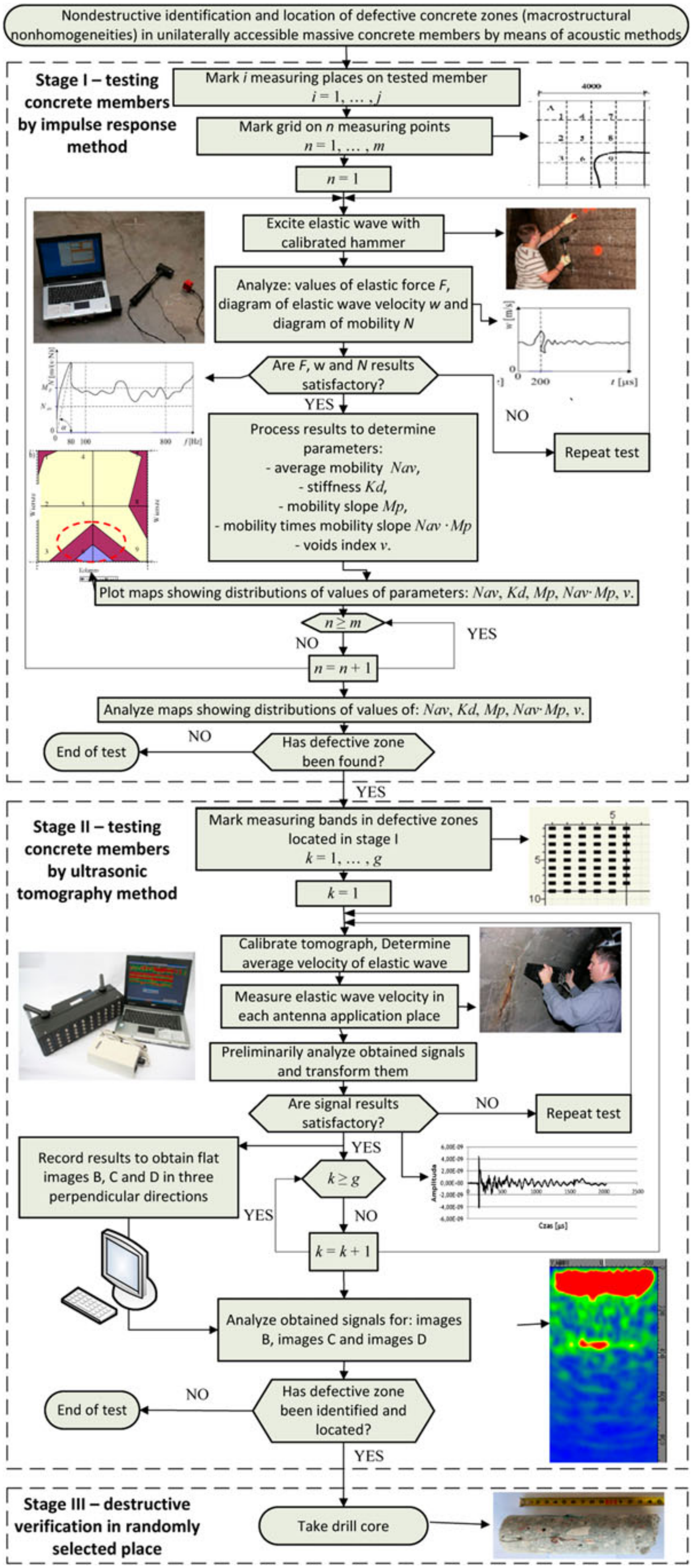


Fig. 3. Flow chart illustrating methodology of nondestructive identification and location of defective zones in unilaterally accessible massive concrete members by means of impulse response and ultrasonic tomography methods

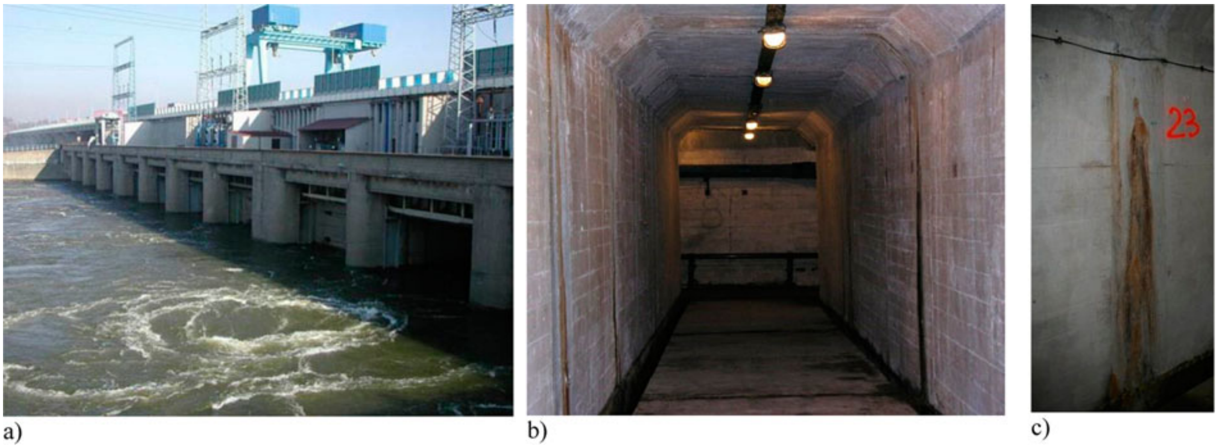


Fig. 4. View of: (a) hydroelectric power plant; (b) access gallery; (c) water leakage on gallery wall

concrete zone can be identified and located along the depth of the tested member through a detailed analysis of images B and D. Image C helps to determine more precisely the depth at which the defect occurs.

In stage III it is recommended to do a destructive verification, for example, by taking a drill core.

4. Example of practical use of proposed methodology

The proposed methodology was used in practice to locate and identify defective zones of concrete in a massive access gallery in a hydroelectric power plant. The tests were carried out in connection with a planned renovation of the power plant. Figure 4 shows the power plant, the access gallery, and a close up of a water leakage on the gallery wall.

4.1. Description of tested wall

During their operation the turbines (each with a power of a few tens of megawatts) make the massive concrete members (including the access gallery walls) vibrate. The gallery walls are made of C25/20 grade concrete with a maximum aggregate size of 32 mm and since they are situated below the water level they should be leakproof. Despite the repeated local sealing, new leaks keep on appearing.

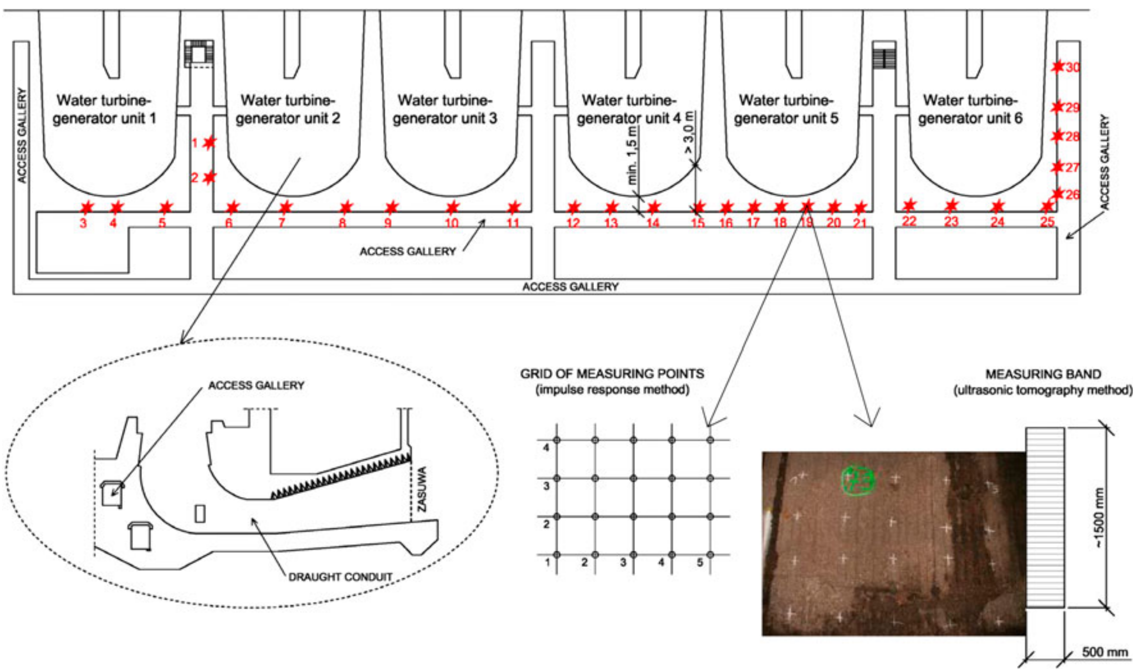
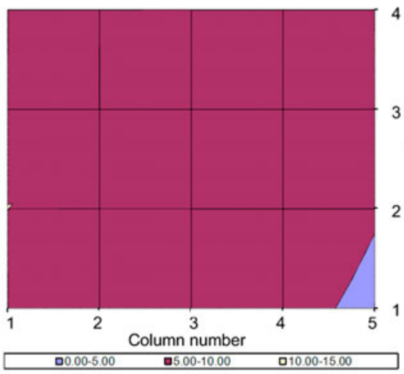
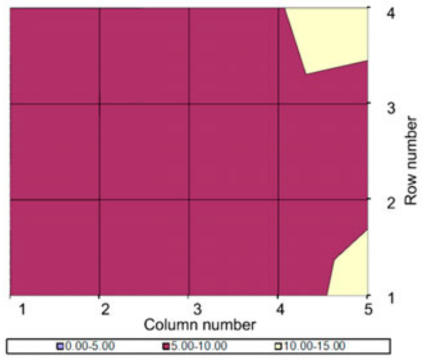
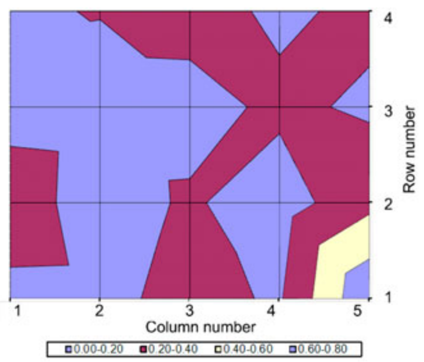
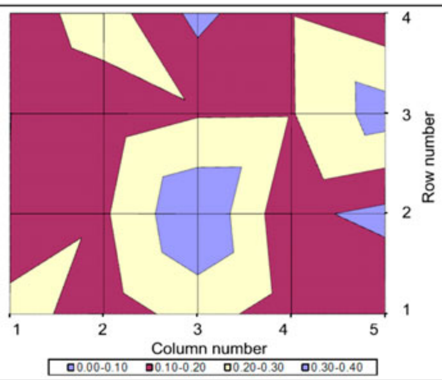


Fig. 5. Location and numbers of measuring places on tested access gallery wall

Table 3. Sample values of characteristic parameters, determined by impulse response method

No.	Number of measuring place/(row no. – column no.)	Parameter symbol				
		N_{av} (m/s·N)	K_d (–)	M_p/N (–)	$N_{av}·M_p/N$ (m/s·N)	v (–)
1	1/(1–1)	1.194	0.069	51.294	1.417	0.410
2	1/(1–2)	1.022	0.039	43.399	1.312	0.505
3	1/(1–3)	0.695	0.069	70.227	1.258	0.547
4	1/(1–4)	0.367	0.050	48.984	0.920	0.536
5	1/(1–5)	0.677	0.080	65.684	2.569	1.391
6	1/(1–6)	0.637	0.087	86.766	2.628	2.449
7	1/(1–7)	0.520	0.085	257.087	0.783	2.751
8	1/(1–8)	0.293	0.116	344.710	1.160	2.081
9	1/(1–9)	3.835	0.010	135.950	1.281	0.449
10	1/(1–10)	3.667	0.030	238.160	1.115	0.644
⋮	⋮	⋮	⋮	⋮	⋮	⋮
1050	30/(4–5)	2.436	0.050	67.180	0.735	0.298

Table 4. Sample test results in form of maps showing distribution of values of parameters N_{av}, K_d, determined in measuring points 3 and 23 by impulse response method

<table>
<tr><th rowspan="2">Parameter</th><th colspan="2">No. of measuring place</th></tr>
<tr><th>3</th><th>23</th></tr>
<tr><td>N_{av}</td><td></td><td></td></tr>
<tr><td>K_d</td><td></td><td></td></tr>
</table>

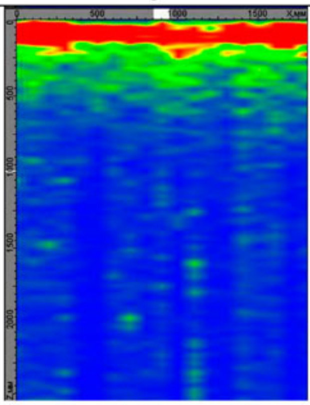
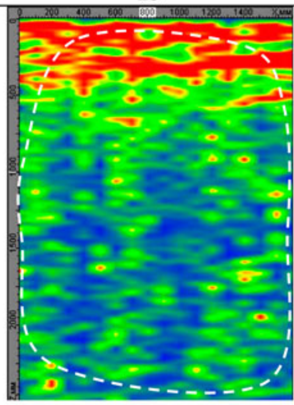
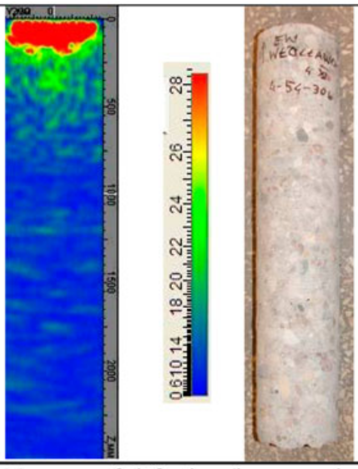
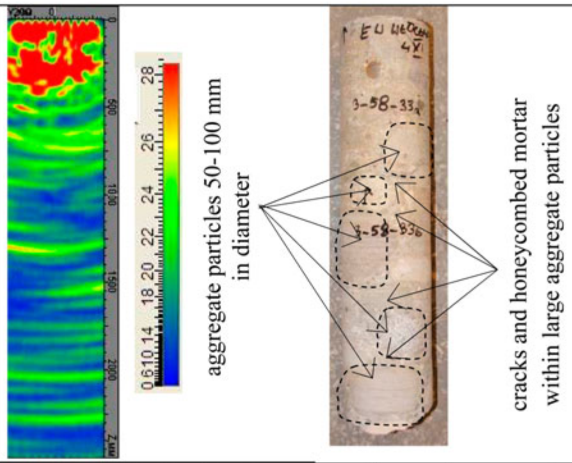
The massive concrete gallery wall, accessible from only one side, was tested in 30 measuring places along its entire length using the proposed methodology. The location and numbers of the places are shown in Figure 5. A grid (4–5 rows and 3–11 columns) of measuring points (in total 1050 measuring points along the entire length of the wall) was marked in each measuring place. The distance between the measuring points amounted to about 500 mm.

The tests were carried out in accordance with the methodology described in Section 4, using first the impulse response method and then the ultrasonic tomography method.

4.2. Results of tests

In the course of testing by the impulse response method in each of the measuring points an elastic

Table 5. Sample test results for measuring places no. 3 and 23, obtained by ultrasonic tomography method

	No. of measuring place	
	3	23
Image D		
Image B with dispersion scale Drill core		
Comments	No zone of defective (honeycombed) concrete was found. The maximum aggregate particle diameters measured in the drill core do not exceed 32 mm.	A zone of defective (nonhomogenous) concrete zone extending to a depth of almost 2500 mm was identified. Aggregate particles with a maximum diameter of 100 mm and cracks and honeycombing at the interface between the particles and the mortar were found in the drill core taken.

wave was excited using a special rubber-tipped hammer and the values of the characteristic parameters: average mobility K_d, mobility slope M_p, average mobility times mobility slope $N_{av}{\cdot}M_p$, and voids ratio v were determined. Sample parameter values determined in 10–20 measuring points are presented in Table 3. On the basis of the parameter values in all the measuring points, maps showing the distribution of the parameter values were plotted. Sample maps for measuring points 3 and 23 are presented in Table 4.

It appears from Table 4 that in almost the whole measuring place no. 3 the value of parameter N_{av} is high, ranging from 5 to 10 m/s·N, whereas within measuring point 5–1 its value is low, ranging from 0 to 5 m/s·N. At the same time the value of parameter K_{d} is high, ranging from 0.4 to 0.8 in most of the measuring place. Therefore, it can be concluded that in measuring place no. 3 a defect in the form of concrete nonhomogeneity is unlikely to occur. This conclusion is confirmed by the map of the distribution of the characteristic parameters, shown in Table 4.

Table 4 also shows that the value of parameter N_{av} is high in almost the whole measuring place no. 23, ranging from 5 to 10 m/s·N, and within measuring points 5–1 and 5–4 it is very high, ranging respectively from 10 to 15 m/s·N. The value of parameter K_{d} is very low, ranging from 0 to 0.2 in most of the measuring place, except for measuring point 3-2 where this parameter ranges from 0.3 to 0.4. On this basis and from an analysis of the map showing the distribution of the characteristic parameters (Table 4) one can conclude that in measuring place no. 23 a defect in the form of a concrete nonhomogeneity is very likely to occur.

Analyses of the results obtained in 30 measuring places showed that, similarly as in the case of measuring place no. 3, in 16 other tested places there are no reservations about the quality of the concrete.

Whereas in 13 tested places, as shown for test place no. 23, defective zones characterized by high concrete nonhomogeneity occur.

Then, in accordance with the proposed methodology, tests were carried out using the nondestructive ultrasonic tomography method. Their aim was to confirm the presence of the defective concrete zones previously detected by the impulse response method and locate them along the depth. The tests were carried out in the measuring places in which defective zones had been located in investigation stage I. In each of the zones, three measuring bands, each 500 mm wide and 1500 mm long, were marked.

Sample test results obtained using the ultrasonic tomograph, showing images B and D in measuring place no. 3 (deemed not defective) and in the defective zones (measuring place no. 23) are presented in Table 5. The defective concrete zone identified in measuring place no. 23 is marked with a dotted line in image D. Table 5 also contains photographs showing the results of exposure in the form of drill cores taken from measuring places 3 and 23. The bottom row of Table 5 contains comments stemming from the investigations.

The results obtained using the ultrasonic tomography method confirmed the results, which had been obtained by the impulse response method. As shown for test place no. 23, the presence of highly porous and nonhomogenous concrete zones was confirmed in 13 of the test places. In the particular zones, the defects were located along the depth of the tested member.

Conclusions

A novel methodology integrating the state-of-the-art acoustic methods of impulse response and ultrasonic tomography for the nondestructive identification and location of zones of defective (honeycombed) concrete in unilaterally accessible massive members has been presented. Since the above nondestructive methods are not commonly used for testing, whereby they are less known, the presentation of the methodology was preceded by a concise description of the methods in order to facilitate their understanding.

Three stages are distinguished in the proposed methodology. In stage I, in which tests are carried out using the nondestructive impulse response method, defective zones in the tested member are identified and superficially located. In stage II, in which tests are carried out using the nondestructive ultrasonic tomography method, the defects detected by the impulse response method in stage I are confirmed and located along the depth of the tested member. In stage III, the results obtained by the nondestructive methods are destructively verified in a randomly selected place.

The provided example of the application of the methodology to a real civil engineering structure has shown the methodology to be useful for identifying and locating defective concrete zones in the unilaterally accessible massive wall of the gallery in the hydroelectric power plant.

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