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Original Research Article

Non-destructive identification of cracks in unilaterally accessible massive concrete walls in hydroelectric power plant

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ABSTRACT

This paper presents a methodology for the non-destructive location and identification of cracks in unilaterally accessible massive concrete walls by means of the state-of-the-art acoustic methods of impulse response and ultrasound tomography. An example of the practical verification of the methodology used to investigate the concrete structure of a hydroelectric power plant is provided.

1. Introduction

Because of their great thickness and the huge mass of concrete they incorporate, the massive walls of hydroelectric power plants are prone to cracking [1,2]. Cracks are understood here as discontinuities in part or whole of the thickness and height of a structural member. Cracks may form when the thermal stresses generated by the exothermy of the cement during the erection of walls exceed the tensile strength of the young concrete. They may also arise as a result of concrete shrinkage. In the course of service cracks in the walls may also appear as a result of, e.g., changes in the temperature of the concrete due to: the cyclic annual changes in the temperature of the water flowing through the hydrotechnical system, the deformation of the soil medium or sustained vibrations generated by the operation of the turbines. Prone to cracking are first of all the wall regions where the concrete is of poorer quality, e.g. is excessively porous due to the separation of the concrete mixture components or its insufficient vibration or because the larger aggregate particles were not entirely coated with the concrete mixture [3]. Cracks can be divided into through cracks (extending across the whole thickness of the wall) and non-through cracks, as illustrated in Fig. 1. Both types of cracks

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adversely affect the safe service of a facility and its durability [4]. If one takes into account the fact that most of the massive walls of hydroelectric power plants are accessible from only one side, it becomes apparent that the location and identification of such cracks, especially the ones invisible from the accessible side, is very difficult.

According to the literature on the subject [5–8], non-destructive methods, e.g. the latest acoustic methods such as ultrasound tomography [9] and the impulse-response method [10], are highly suitable for the location and identification of cracks in unilaterally accessible walls. The methods are increasingly used in the diagnosis of massive structures made

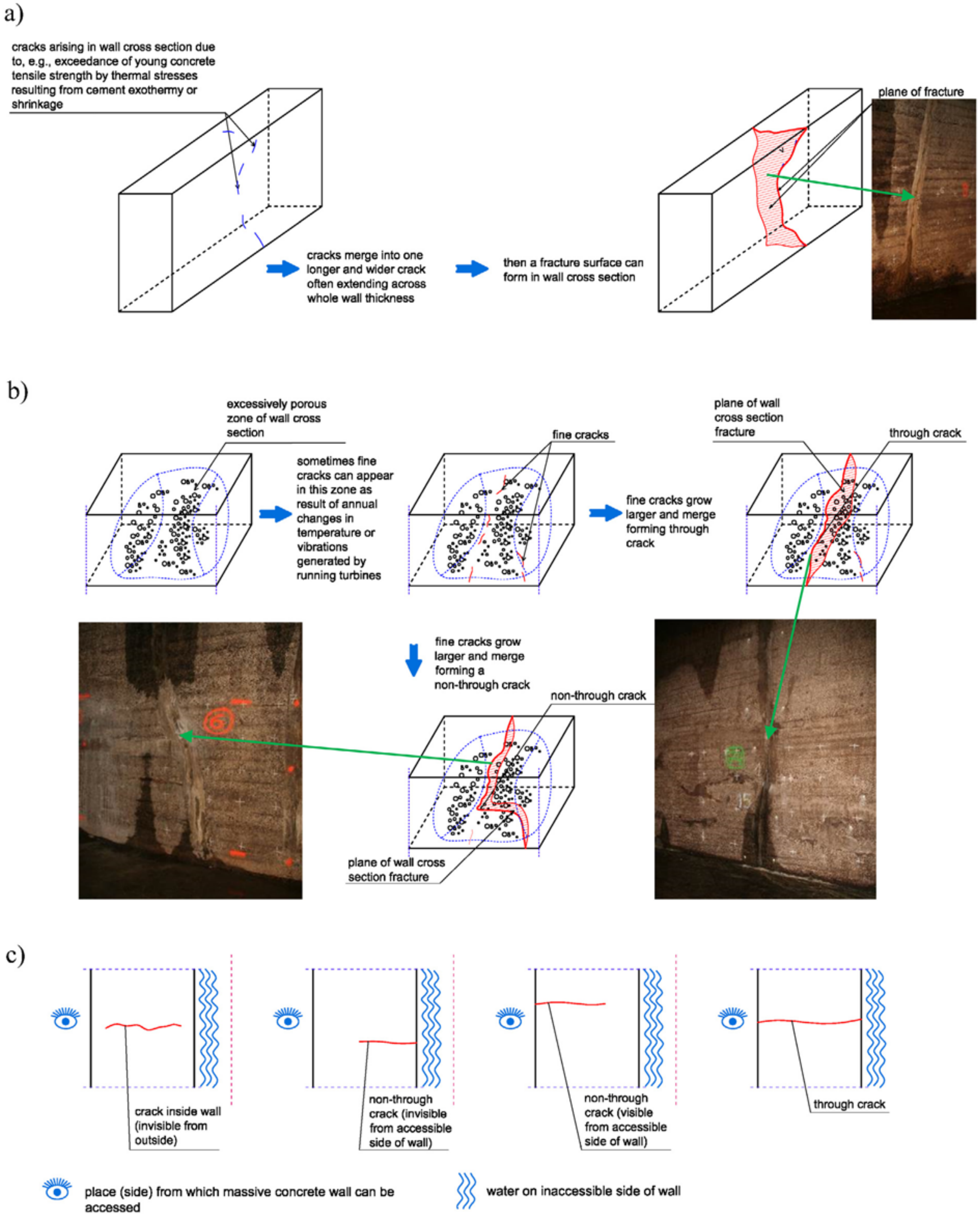

Fig. 1 – Typical cases when cracks arise in massive concrete walls: (a) at construction stage; (b) during service; (c) possible courses of cracks in wall cross section.

of concrete [11–14]. The authors of [15,16] propose ultrasound tomography for the identification of cracks in unilaterally accessible concrete members while the authors of [17–20] recommend the impulse response method. In [21,22] the impact-echo method is proposed for this purpose.

The present authors in [3] proposed to use two of the above methods, i.e. the impulse response method and ultrasound tomography, to non-destructively locate and identify defective zones in massive concrete members accessible from only one side. Also an original methodology suitable for this purpose was developed [3].

A literature survey was carried out and it was found that no cases of the location and identification of cracks in unilaterally accessible massive concrete walls by means of combined non-destructive methods have been reported so far. Also no methodology has been developed for such tests.

Considering the above, the authors have developed a methodology for the non-destructive location and identification of cracks in unilaterally accessible massive concrete walls by means of the non-destructive impulse response method and ultrasound tomography, which is presented in this paper. The proposed methodology has been verified in practice through tests carried out in a hydroelectric power plant.

2. Description of proposed methodology

As mentioned in [10], the impulse response method is suitable for the quick searching of large concrete surfaces and the approximate location of cracks in 500–1000 mm thick unilaterally accessible members with no possibility of assessing the depth at which the crack occurs. Such a possibility is offered by ultrasound tomography [23–25] owing to which one can spatially locate and identify cracks in up to 2500 mm thick massive members. Therefore it seems sensible to combine the two methods.

A general chart and a detailed chart of the methodology for the non-destructive testing of unilaterally accessible massive concrete walls aimed at locating and identifying cracks by means of the combined impulse response method and ultrasound tomography are presented in Figs. 2 and 3 respectively.

As Fig. 3 shows, it is proposed to conduct the investigations in three steps.

In step I, test places should be randomly selected on the surface of the investigated massive concrete wall. It is recommended that the places cover no less than 40% of the wall surface area.

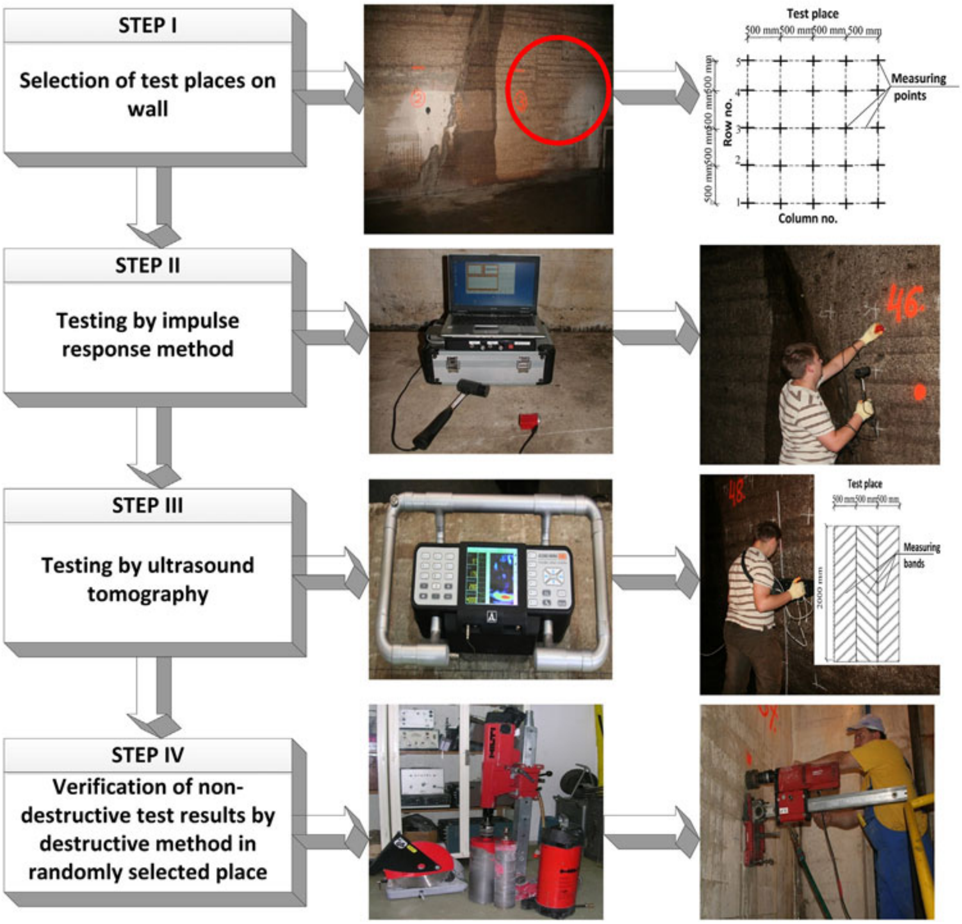

Fig. 2 – **General chart illustrating methodology developed for non-destructive testing of unilaterally accessible massive concrete walls aimed at locating and identifying cracks.**

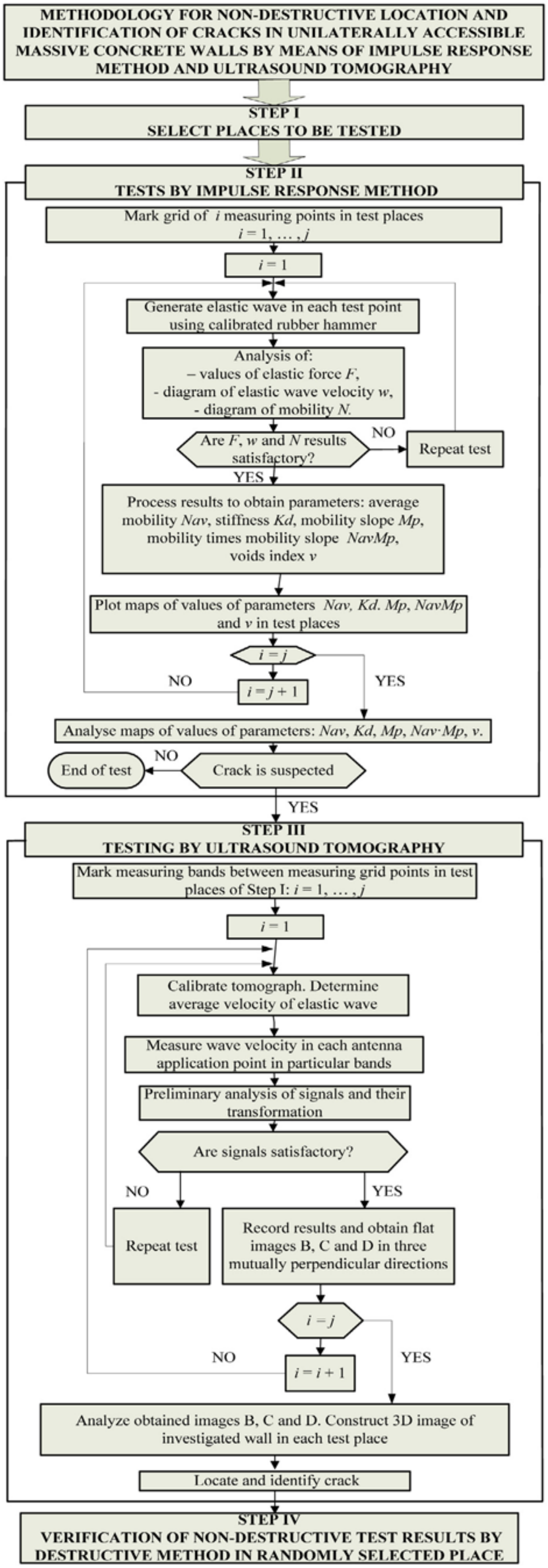

Fig. 3 – Detailed chart of methodology for non-destructive location and identification of cracks in unilaterally accessible massive concrete walls by means of impulse response method and ultrasound tomography.

In step II, tests are conducted to approximately locate cracks. For this purpose one should mark a grid of i measuring points spaced at every 500 mm in each test place on the surface of the investigated wall. The measuring grid should extend along the whole height of the wall and if this is not possible, it should cover a wall fragment with at least its five rows and 5 columns, as shown in Fig. 2. Then an elastic wave should be generated in each measuring point of the grid by means of a calibrated rubber hammer with load cell and should be registered by transducer. As mentioned in [10] if testing on a roughened or grooved surface, position the transducer on its tripod support so that no rocking of the transducer base occurs. After that the value of the elastic force F generated by the hammer, the diagram of elastic wave velocity w and the diagram of mobility N should be analyzed. In [10,13,17] one can find conditions which need to be satisfied in order for the obtained results to be deemed satisfactory. If the results are satisfactory, then using the dedicated software they should be processed in order to obtain the values of the characteristic parameters based on mobility diagram, i.e. average mobility N_{av}, dynamic stiffness K_d, mobility slope M_p, average mobility times mobility slope $N_{av} \cdot M_p$, voids index v, in each of the measuring points. Then maps of the distribution of the values of the parameters in each of the test places on the surface of the investigated wall should be plotted. As mentioned in [10] and explained in the example below through a detailed analysis of the maps one can approximately locate the areas on the surface of the investigated wall where it is suspected that there is crack.

In step III, ultrasound tomography is employed to confirm the suspicion of the presence of the crack located by the impulse response method and to locate and identify it precisely in the wall cross section. The grid of measuring points adopted for the impulse response tests should be used again and measuring bands, each 500 wide, should be marked on the grid, as shown in Fig. 2. If a crack has been approximately located by the impulse response method, it is from this place that one begins to mark the bands. There should be at least 3 bands. Then having calibrated the ultrasound tomography one should measure the ultrasonic wave velocity in each of the antenna application points. In the course of the measurements the signals are preliminarily analyzed to check whether it is possible to locate and identify the crack on their basis. If this not the case, the testing should be repeated. If this the case, then the signals should be transformed using the dedicated software. The transformation consists in compiling the data recorded for a given measuring band. If the results are satisfactory, they are recorded and flat images B, C and D are obtained in three mutually perpendicular directions. The images show the inside of the massive concrete wall in the given test place. By examining images B and D in detail one can locate and identify the crack along the depth. Image C helps to determine more precisely the depth at which the crack occurs.

If there is a crack visible on the wall surface, but it is not known how deep it is, then in order to identify it (determine its

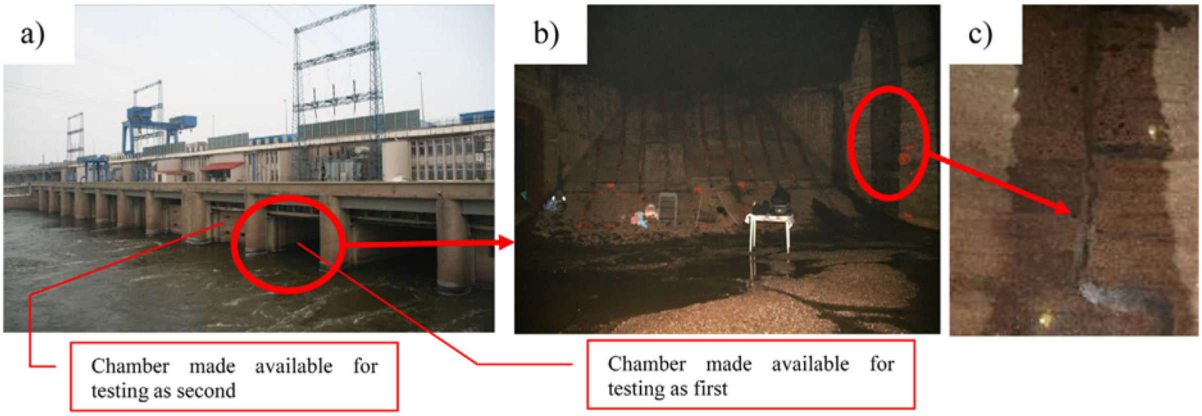

Fig. 4 – View of: (a) hydroelectric power plant with indicated chamber investigated as first, (b) fragment of investigated wall, (c) cracks.

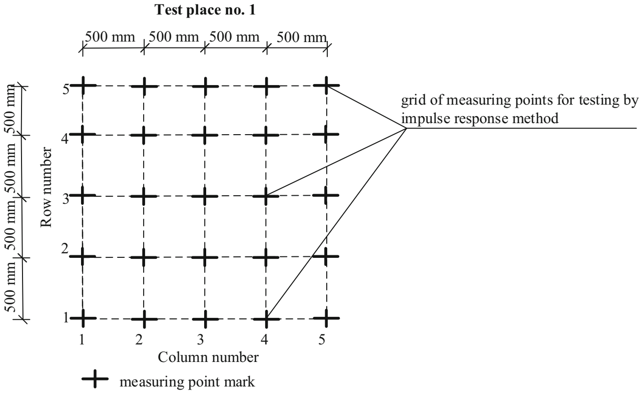

Fig. 5 – Numbering of measuring points in test place no. 1.

course in the wall cross section) one should carry out the ultrasound tomography tests being part of step III.

In step IV it is recommended to carry out destructive verification, e.g. by drilling a core.

3. Practical verification of the methodology

3.1. *Introductory information*

The methodology was verified in a hydroelectric power plant which was to undergo repairs. Fig. 4 shows a general view of the power plant, a fragment of the unilaterally accessible chamber wall investigated as first and a close-up of one of the cracks visible on its surface. The wall, about 2500 mm thick and about 6000 mm high, was made of C25/30 grade concrete with the maximum aggregate size of 32 mm.

The investigations were done in accordance with the methodology described in Section 2: first places to be tested were selected and then tests using the impulse response method and ultrasound tomography were carried out.

The investigations carried out in three characteristic test places, denoted as 1, 2 and 3, selected from many such places are presented below. No cracks were visible on the wall surface in test places no. 1 and 2, whereas a crack was visible in test place no. 3. The temperature in investigated places was around

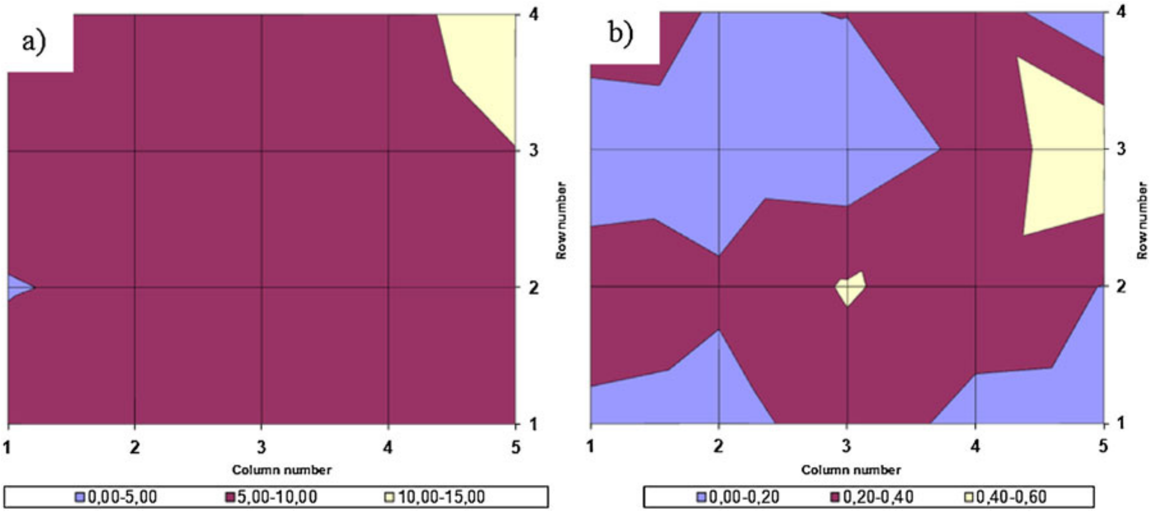

Fig. 6 – Exemplary maps of parameter values determined by impulse response method in test place no. 1: (a) parameter N_{av}, (b) parameter K_d.

20 °C ± 3 °C, were ventilated while test places and the surfaces of the investigated walls were dried.

3.2. *Test results and their analysis*

3.2.1. *Test place no. 1*

A grid of measuring points forming 5 rows and 5 columns was marked in test place no. 1 in order to carry out impulse response tests. The measuring points were spaced at every 500 mm as shown in Fig. 5.

During testing by the impulse response method an elastic wave was generated in each of the measuring points by means of a properly calibrated rubber-tipped hammer and the values of the characteristic parameters: average mobility N_{av}, dynamic stiffness K_d, mobility slope M_p, average mobility times mobility slope $N_{av} \cdot M_p$ and voids index v, were registered.

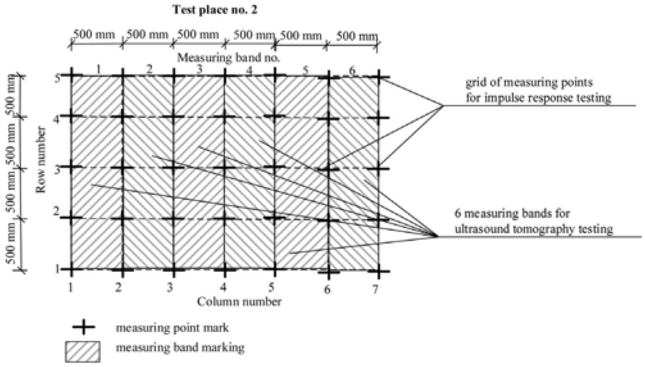

Fig. 7 – Numbering of measuring points and bands in test point no. 2.

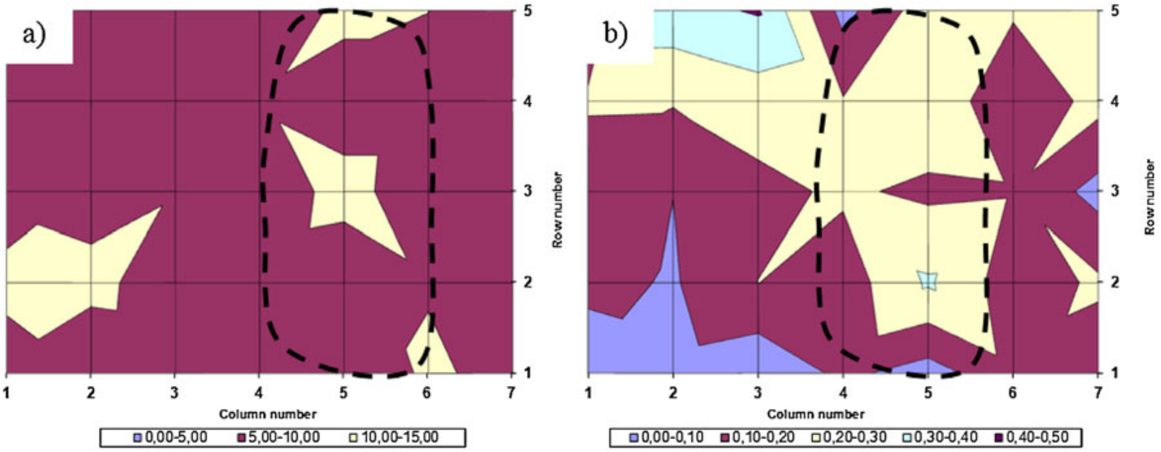

Fig. 8 – Exemplary maps of parameters determined by impulse response method in measuring place no. 2: (a) parameter N_{av}, (b) parameter K_d.

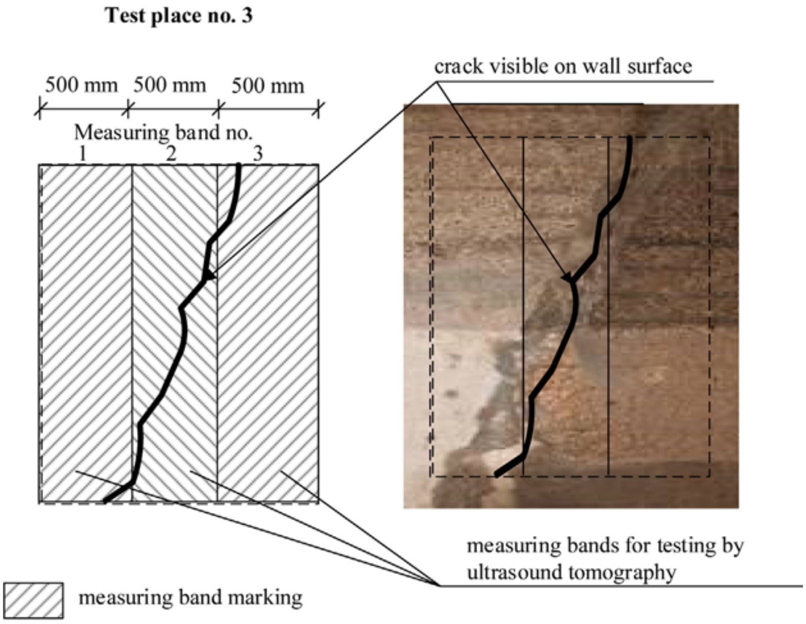

Fig. 9 – Numbering of measuring bands in test place no. 3.

Then maps of the values of the parameters were plotted in test place no. 1. Fig. 6 shows such maps for parameters N_{av} and K_d.

It emerges from Fig. 6 that in almost the whole test place no. 1 parameter N_{av} is characterized by high values, ranging from 5 to 10 m/s N, whereas parameter K_d is characterized by low values, ranging from 0 to 0.4 in most of the test place area.

As also mentioned in [10] the following conclusion emerges from the investigations: the absence of jumps in the value of parameter N_{av} and of significant changes in parameter K_d within the entire test place indicates that there is no crack in this place.

3.2.2. *Measuring place no. 2*

As shown in Fig. 7, a grid of measuring points forming 5 rows and 7 columns was marked in test place no. 2 in order to carry out impulse response tests. Similarly as in the case of test place no. 1, the measuring points were spaced at every 500 mm.

During testing by the impulse response method, similarly as in test place no. 1, an elastic wave was generated in each of the measuring points and the values of the characteristic parameters were registered. Then maps of the parameter values, shown as illustration for parameters N_{av} and K_d in Fig. 8, were plotted.

It emerges from Fig. 8 that parameter N_{av} is characterized by high values, ranging from 5 to 10 m/s, in almost the whole test place no. 2 and in measuring points 6-1, 5-3 and 5-5 it reaches a very high value of 10–15 m/s N. Whereas parameter K_d has a very low value of 0-02 in a large part of the test place, except for measuring points 5-2, 5-4, 5-5, 4-3 and 4-4 where its value amounts to 0.2–0.4 and except for points 3–5 where it amounts to 0.4–0.5.

The following conclusion emerges from the investigations: the results indicate that there may be a crack between columns 4 and 6.

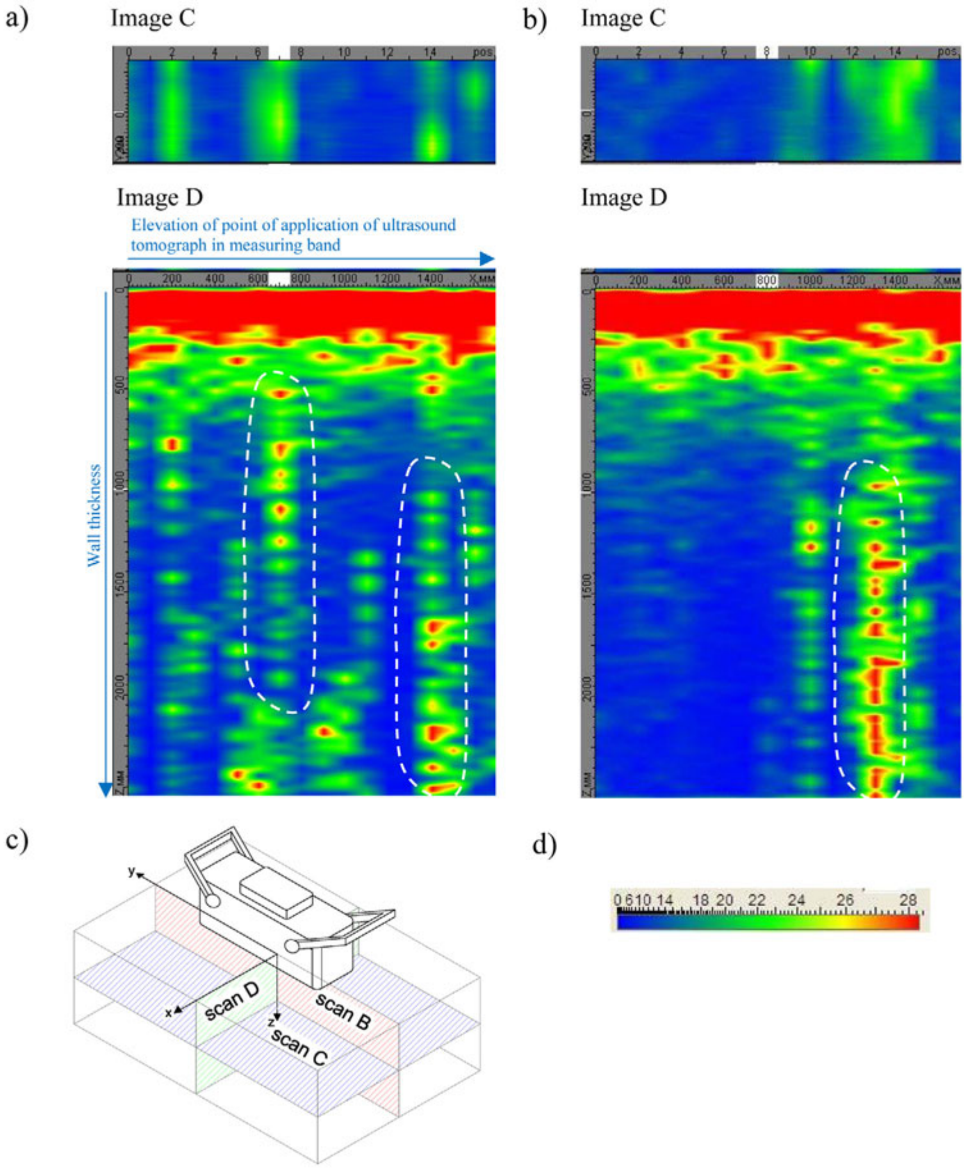

Fig. 10 – Test results obtained using ultrasound tomography in test place no. 2 in measuring points: (a) no. 4 and (b) no. 5, system of images adopted for investigated wall (c) and scale of ultrasonic dispersion (d).

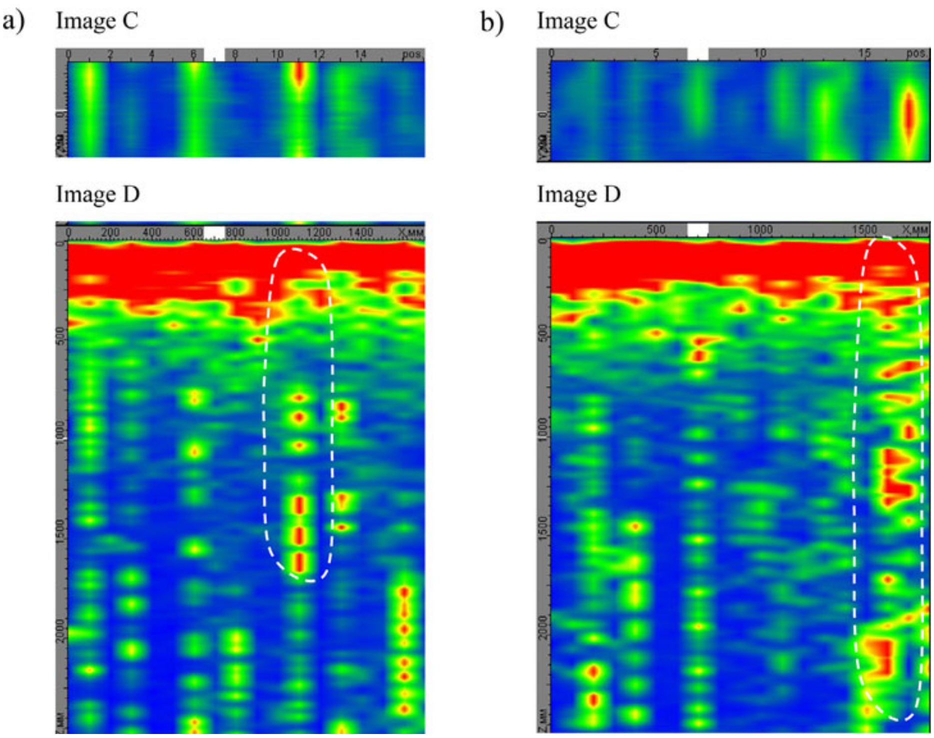

Fig. 11 – Ultrasound tomography test results obtained in test place no. 3: (a) in measuring band 2, (b) in measuring band 3.

Considering the above, six measuring bands were marked in test place no. 2 (Fig. 9) and ultrasound tomography tests were carried out there to confirm the suspicion of the presence of the crack located by the impulse response method and to identify the crack (determine its course in the wall cross section). The results obtained by means of an ultrasound tomography, in the form images C and D, are shown in Fig. 10. The broken line in images D marks the cracks identified in measuring bands 4 and 5. The figure includes the system of images adopted for the investigated wall, and an ultrasonic dispersion scale.

The following conclusion emerges from the investigations: ultrasound tomography confirms the presence of cracks invisible on the surface in the considered measuring bands no. 4 and 5. An analysis of images D shows that the cracks start at a depth of about 500 mm from the wall surface and run further into the wall to a depth of about 2500 mm.

3.2.3. *Test place no. 3*

In accordance with the methodology described in Section 2, only ultrasound tomography tests were carried out in test place no. 3 where a crack is visible on the surface.

The ultrasonic tomography test results, in the form of images C and D, for measuring bands no. 2 and 3 are shown in Fig. 11. The identified crack is marked with a broken line in images D.

The following conclusion emerges from the investigations: an analysis of images D shows that in test place no. 3 the crack extends into the wall cross section to a depth of about 1700–2500 mm. It should be expected that this crack is a through crack.

Finally, it should be explained that, there was no need for the destructive verification of the results obtained in test places 2 and 3 according to the presented methodology. After the tests in this chamber the neighbouring chamber (Fig. 2), situated on the other side of the investigated wall, was made available for testing. A visual inspection showed that the cracks in test places 2 and 3 in the chamber, identified as through cracks actually were such cracks.

4. Conclusion

An original investigative methodology for the location and identification of cracks in unilaterally accessible massive concrete walls, exploiting the state-of-the-art acoustic methods of impulse response and ultrasound tomography, has been presented.

Three main steps are distinguished in the methodology. Step I includes the selection of test places on the wall surface. Step II includes testing by the non-destructive impulse response method in order to approximately locate the areas on the wall surface, in which it is suspected that there are cracks. Step III includes testing by the non-destructive method of ultrasound tomography in order to confirm the suspicion of the presence of the crack previously located by the impulse response method and to precisely identify the crack in the wall cross section.

The example of the application of the methodology to a real facility confirmed its practical usefulness. In the example, the results of the investigations for three characteristic cases were presented. In the first and second case there were no visible cracks on the wall surface. In the second case, tests carried out using the impulse response method and ultrasound tomography revealed cracks in the wall cross section and indicated the depth to which they extended into the wall. In the third case, in which a crack was visible on the wall surface, the depth along which it ran into the wall was identified.

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