Identification of concrete voids in an untypical railway bridge pillar by Ground Penetrating Radar Method

Abstract

The article presents the results of non-destructive testing, which was carried out on the concrete pillar with an unusual, trapezoidal shape and densely spaced reinforcement. After stripping the formwork, some surface voids became visible, which suggested that the existence of subsurface voids was also probable. The Ground Penetrating Radar method (GPR) was used to state whether these voids are formed and possibly to determine their approximate location. This paper discusses the adopted methodology of measurements, analysis and the GPR data processing. The interpretation of the echograms was based on a comparison of recorded GPR data with the modelling results MRS (FD) of electromagnetic wave propagation with the known geometry of the tested pillar. The results of detection are shown mainly in the form of the echograms (B-SCAN) and are collected as a cumulative sketch (C-SCAN). In order to assess the impact of the identified voids on the bearing capacity of the structure, the shell model of the pillar was built with the use of FEM. It shows stress distribution differences in the pillar with a continuous internal structure and in the pillar with the modelled voids. The obtained results were used for checking the bearing capacity of damaged pillar and during the preparation of the effective repair program.

Keywords: NDT, GPR, bridges, reinforced concrete, void identification.

1. Introduction

Pillars in many bridges, particularly railway, which are subjected to larger and more dynamic loads, are usually heavily reinforced with densely spaced bars of large diameter. In addition, if they are located in an urban area, their shape may not be typical. This may be either due to the space constraints and the needs to bypass the terrain obstacles or just to realize ambitious visions of architects. In such structures, a proper distribution of the concrete mix may be difficult. The mistakes committed at this stage may result in excessive number of pores and the spaces not filled with concrete mix. The possible appearance of voids within the concrete element may be identified with the use of a variety of testing techniques including NDT. One of them is a geophysical GPR method based on the emission of electromagnetic waves with frequency ranging from short to ultra-short radio waves and with the recording of reflected waves from layers characterized by changes in dielectric properties. Despite the great potential and many applications of this method, its effectiveness is often determined by the conditions of signal propagation in a given element.

The radar methods are well-established among diagnostic technologies in the field of NDT&E, and becoming an increasingly used tool in testing and inspection of bridge structures. Support settlement, span deflections and bridge vibrations can be measured with the use of the ground-based radar interferometry ([5], [8], [9], [10]). In addition to this, the movement of the bridge solids (supports and spans) on the deforming terrain caused by mining activities can be assessed using the satellite radar interferometry InSAR [11]. In case of a need to identify the internal structure of the elements – Ground Penetrating Radar (GPR) technique [7] can be used. The subject of such identification may be, for example, the reinforcing bars or prestressing tendons ([1], [4], [7]). Often the purpose of explorations are the voids resulting from the faults during concreting ([14], [13]) or ineffective injection of already existing voids ([3], [6], [15]). This may be caused by either adverse vertical deviation from the formwork or high density of reinforcement (Figure 1).

The theoretical potential of GPR method in the identification of internal structure is generally known [2]. However, in the case of heavily reinforced concrete structures, often the test result can be difficult to read and evaluate. The electromagnetic wave in the area of heavy reinforcement is subjected to dissipation, damping and imposing, so the resulting image does not always give the opportunity to unambiguous interpretation of the content [1]. The solution of this problem may be an additional modelling MRS (FD) of electromagnetic wave propagation with a known geometry of the tested pillar. It is a reference image with respect to the profiles obtained in the field. The main aim of this article is to present the methodology of measurements and processing the GPR data used for the identification and location of voids in the railway bridge pillar. In addition, results of FEM analyses which were carried out with the use of the GPR recognition technique, are presented. They show the qualitative differences in the stress distribution depending on the existence of voids in internal structure. This allowed to carry out a more reliable calculation of bearing capacity of poorly concreted pillar and configuration of an appropriate repair program. During its implementation at the construction site, the voids existence was confirmed.

2. Basic parameters of the analysed pillar

The cross-section of the railway viaduct with the analysed support is shown in Figure 2. It is a seven span bridge with continuous, composite steel-concrete superstructure. The theoretical spans range from 16 to 24 m and the total length is approximately 140 m.
Due to a large angle between the railway line and the obstacle the pillars are also positioned diagonally. Their unusual shape and arrangement results from the construction technology involving the transverse launching of the prefabricated structure. This solution was enforced by the railway administration which strove to minimalize the breaks in the train timetable.

The analysed support has trapezoidal shape and its larger base is located on the footing (Figure 3). The areas vulnerable to the voids mainly included its lower part, especially near the front surfaces (Figure 4, Figure 5). The pillar is reinforced on both sides with 25 mm bars with the spacing of 100 mm.

3. Apparatus and measurement parameters

The GPR method, which records the echo of an electromagnetic wave emitted into the structure, enables testing of natural or man-made structures. Due to the characteristic frequency of the signal, the antenna allows the profiling with the vertical resolution ranging from 2.5 to 3.5 cm (at the wave speed in the centre at the level from 10 to 14 cm/ns). The choice was dictated by the dimensions of the potential voids.

There are three basic methods of measurement with the use of GPR: reflection probing, velocity profiling and screening. The study of the support used the first of the distinguished measurement modes (B-scan). Recording of traces was performed at the intervals of 1 cm. The length of the time window (time of recording of a single probe pulse) set in the test area was 31 ns, which, with the assumed velocity of a wave in concrete of 10 - 14 cm/ns, gave the extent of the structure penetration to a depth of more than 1.5 m (thickness of the pillar is 70 cm). The return signal sampling frequency was 13 GHz and the number of stacks was 32.

4. Research methodology

Horizontal profiling was performed on northern and southern side. Profiling at intervals of 15 cm was assumed in all test areas. The passage of the antenna was done in a direction away from the vertical axis of the pillar to the outer frontal plane. In each of the passages, the antenna was moved in the lane between the designated profile lines. The number of the top line is identical with the name of the registered profile. Additionally, in each test region, diagonal profiling parallel to the frontal plane was performed. 5 profiles on the area at intervals of 20 cm were performed. In this case, the number of the left line located near the frontal plane corresponds to the name of the recorded profile. The geometric distribution of profiles with photos of relevant test areas is shown consecutively on Figure 6, Figure 7 and Figure 8.
5. Methodology of GPR data evaluation

To get information on the mapped void in the reinforced concrete element, simulation of wave propagation EM was carried out assuming similar geometry of the element to the geometry of the real support (Figure 9a). The model includes the actual spacing of the reinforcement and two air voids in the central area of the cross section. The voids remained in the relationship 2:1 (the ratio of the surface areas in a side view), which were similar to the shape of the lens. The larger void was 50 cm wide and 12 cm high. This assumes homogeneity of medium in which the signal propagated. MRS (FD) modelling was conducted by choosing the parameters of the procedure corresponding to the parameters of the echograms obtained during the field measurements. All operations of GPR echograms processing were performed with the use of the program Reflex-Win.

Both - echogram resulting from the simulation and echograms recorded in the field - were subjected to the same filtration procedures:

- 1D, i.e. the removal of the GPR signal constant component, the removal of low frequency noise by subtracting the mean of the sample in a given time window of a single trace,
- 2D, i.e. the removal of the mean of the trace, the bandpass filtration and Stolt f-k migration [12] and signal amplification based on the mean of the amplitude distribution curve.

The results of the filtration (without Stolt f-k migration) of the echogram, which confirms the potential possibility of identification of the voids in the data obtained in-situ. Due to a more complex shape of the contour of the cross-section and a larger amount of reinforcement in the tested pillar, an additional simulation of wave propagation EM was prepared. The modelling was performed with respect to the cross-section for which the GPR profile no. 34 was realised (compare Figure 7). Model geometry and theoretical echogram of the profile no. 34 after filtration are shown in Figure 9b.

In the modelled element, the image of a void is clearly visible on the echogram, which confirms the potential possibility of identification of the voids in the data obtained in-situ. Due to a more complex shape of the contour of the cross-section and a larger amount of reinforcement in the tested pillar, an additional simulation of wave propagation EM was prepared. The modelling was performed with respect to the cross-section for which the GPR profile no. 34 was realised (compare Figure 7). Model geometry and theoretical echogram of the profile no. 34 after filtration are shown in Figure 10a and Figure 10b.

No significant anomaly can be distinguished in the model echogram of the profile no. 34, and the image is (in two main areas) comparatively homogenous. The result of modelling (Figure 11a) was confronted with the echogram recorded on site for the profile no. 34 (Figure 11b). In a real image at a distance ranging from 0.5 to 0.7 meter from the beginning of the profile (x axis - DISTANCE) and at a depth of 0.3 m (y axis - DEPTH), a strong anomaly appears, which is not disclosed in the model. Few similar observations were reported mainly in the adjacent profiles until no. 34, and also in other test areas.

6. Results of identification

The analysis and interpretation of all echograms in all test areas was conducted on the basis of obtained simulation results.

In the test area no. 1, from the north side of the pillar, an attention should be paid to the vertical profiling. Particularly important is the profile no. 21 along the length from 0.3 to 0.8 m (measured from the beginning - x axis - DISTANCE), where at a depth ranging from 0.2 to 0.5 m (y axis DEPTH), there is a significant strengthening of the radar signal (Figure 12). It is much stronger than the surrounding background. Another zone with a strong anomaly located at a depth from 0.2 to 0.35 m in the range from 1.2 to 1.4 m. Unfortunately, the proximity of the external, surface discontinuity of (compare Figure 7) in this zone does not guarantee the source of this disturbance, especially with a strong reflex at a depth of 0.50 m. The strength of the first anomaly decreased at the further profiles, but it was still visible.

The second anomaly also clearly appeared on the profile no. 23 and less on profiles no. 24 and 25, where it displaced to the right and occurred at a distance from 1.5 to 1.6 m.

In the measurement area on the south side of the pillar (test areas no. 2 and 3), the authors paid attention to the horizontal profile no. 6 and 7 (Figure 13) at a distance from 0.5 to 0.7 m and at a depth from 0.4 to 0.6 m. Additionally, an important profile in the horizontal profiles turned out to be the area of the profile no. 12 and 13 (Figure 14) with the horizontal coordinate of 1.6 m and vertical (depth) of 0.40 m. On the vertical profiles of this area, particularly relevant were sections no. 22 and 23 (Figure 15), where a significant anomaly corresponds to the horizontal coordinate from 0.5 to 0.6 and vertical from 0.3 to 0.4 m. In the measurement area on the external side of the pillar 1 in the lower zone (test area no. 3), anomalies occurred in the profile no. 32 (Figure 16), 34, 36, 37 along the length from 0.5 to 0.8, where from a depth of 0.4 m strong broad repetitive signal reflection appeared.
The indicated areas on Figure 17 show the location of identified major anomalies on particular echograms. At the stage of GPR data interpretation, the authors were not totally certain of the actual existence of these voids. A more precise identification was difficult due to the surface defects of the support and a high density of reinforcement. Therefore, all areas with potential damages were taken into account in further analyses.

7. The impact of the identified voids on the stress distribution and bearing capacity of the pillar

To assess the impact of the identified voids on the stress distribution and bearing capacity of the pillar under the realistic load, the shell model (Figure 18) with the use of FEM [10] was built. For simplicity, it was assumed that there is an internal void with the thickness of 40 cm in all areas identified with the radar measurement (Figure 17). The calculations were carried out in linear material model of concrete. It was assumed that all surface defects are properly removed by repair mortars and therefore were not taken into account in the analysis.

Figure 19 shows the generated maps of vertical stresses from the unit load, which illustrates how a qualitative change of their distribution due to the presence of voids looks like. From this approximate analysis it can be seen that in the calculations of the bearing capacity of the pillar different stress distribution should be taken into account.

In the further section of the analysis, a simple verification of stresses was carried out at the maximum effort of the pillar. The reaction from the superstructure in the most unfavourable load combination of dead and live loads was taken into account. Presence of voids caused an increase in the stresses in concrete by about 2 MPa. The pillar was designed with a significant reserve in the capacity. Verification of the bearing capacity according to the Eurocode [16] also confirmed that the voids do not directly threaten the safety of the entire bridge. However, they can contribute to reducing the stability of the pillar and reduction of its fatigue load capacity due to the formation of the notch.

Therefore, it was finally decided to implement the repair program. It consisted of filling the voids with the cement injection. The drilled holes confirmed the existence and location of the identified voids, and the amount of used cement mortar matched the estimated size of these voids.
8. Conclusions

The instrumentation and the type of data filtration proved to be effective despite the presence of obstacles in the form of dense reinforcement and surface defects of the pillar. The approach based on the correlation of the results of wave propagation modelling and the actual measurement were very helpful. This methodology seems to be the right approach for this type of inspection works. However, the actual measurement data is much less clear and unambiguous in response and thus much harder to interpret in comparison to theoretical (model) signal.

The calculations of the support with the use of FEM showed the possibility of unfavourable stress redistribution. It was taken into account during the control calculations of the bearing capacity. The conducted non-destructive tests helped to clarify the repair program and the ranges of necessary cement injections while reducing the number and depth of required outcrops and boring holes. In this light the presented results from the practical point of view, are a valuable case study illustrating the capabilities of GPR method to identify the construction defects in the concrete structures.

In further works aimed at improving the discussed above methodology, other non-destructive techniques will be applied. One of them is an ultrasound technique that can be used to confirm the results from the GPR scanning. There are also plans to use the GPR in the tomographic mode which was not possible in the described experiment as the situation on the construction site during the measurements prevented the access from both sides of the pillar.

9. References

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