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Evaluation of precast pre-post-tensioned concrete bridge beams with the use of GPR method

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Abstract

Precast pre-post-tensioned concrete beams are commonly used in transport engineering. Significant number of bridge structures is being built with the use of precast girders due to their advantages such as quick construction process, moderate cost and reduction of scaffolding and shuttering works. To avoid failures, precast structural members must be subjected to strict quality control that requires the use of the non-destructive testing methods. One of the most suitable NDT methods for precast girders inspection is the Ground Penetrating Radar method.

The aim of the research described in this paper was to evaluate the parameters of prefabricated 'T' bridge girders with the use of the Ground Penetrating Radar method. The beams were investigated upon the producer's request in order to assess the correctness of the production process. The georadar measurement was conducted and the raw data were processed with dedicated software. As a result of the study, a series of radargrams were attained. Based on these data, the rebar location and cover depth as well as pre-tensioning and post-tensioning cable trajectories were determined. The results allowed defining capabilities and limitations of the Ground Penetrating Radar method with regard to quality control of prefabricated concrete elements.

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Keywords: GPR, prefabricated pre-stressed beam, prefabricated post-stressed beam, cable trajectories

1. Introduction

Poland's first pre-tensioned concrete bridges were constructed over the canals of the Trynka River in Grudziądz in years 1955-1956 with the first prestressed concrete beams manufactured at the Precast Concrete Plant in Kraków Czyżyki [1].

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The popularity of the prestressed concrete was evolving with time to reach a phase of rapid development. Today pre- and post-tensioned concrete beams are being widely used in transport infrastructure and in buildings.

A high degree of complexity makes structural elements particularly sensitive to bad workmanship. It is thus important to detect errors as soon as possible as they may have a substantial influence on bearing capacity and durability of the beams. Particular attention should be paid to precast concrete plants, where the elements are produced. Quality control of prestressed beams focuses primarily on:

- checking cable ducts for blockages
- measuring cover thickness with a cover meter
- testing compressive strength of concrete with a Schmidt hammer

These procedures fail to provide sufficient information about the reinforcement arrangement or cable duct trajectory after grouting and stressing. This problem can be solved by the use of a radar method for prefabricated concrete beams testing as it was presented in following papers [2-5] .GPR method widely accepted is continuously developed and improved.

2. Radar method.

The radar method measurements use electromagnetic waves emission into the material and record reflected signals at the boundaries of the media comprising the environment, with different electric parameters. The propagation of radio waves in the frequency range characteristic of the radar method is described by the classical electromagnetic field theory. The radar method-related issues have been thoroughly presented in the literature, [6], [7]. The method uses a georadar (GPR). The most commonly applied GPR is an impulse georadar, which generates electromagnetic waves in the form of pulses with specified frequency. The penetration depth depends on the signal strength, which is, however, limited for user safety reasons. The probing impulse is transmitted over time duration from 0.5 to 10 ns and the signal echo is detected between the pulse intervals [8]. The measurement uses the reflection mode of profiling, where both antennas (transmitting and receiving) are placed in parallel and moved perpendicular to the marked out measurement profile. The electric field is polarized in parallel to the longer axis of the antennas. The spacing and orientation of antennas substantially affect the wave image recorded. It is important to maintain the shift steady when triggering the signal at the constant time interval [8].

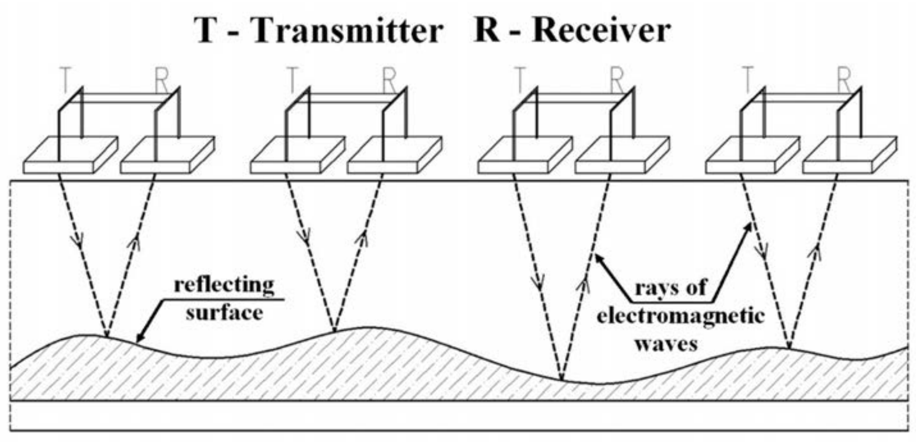

Fig. 1. Reflection profiling.

The accuracy of radar surveys is dependent on the horizontal and vertical resolution, and is determined based on the interrelation between two return pulses [8].

Prior to the survey, the georadar has to be properly calibrated by establishing:

- the length of time window and number of samples in the trace
- the number of signal sums
- the mode and interval of trace records
- the frequency of signal sampling

Relevant principles and procedures for correct determination of these parameters are included in [8] and [9]. The data obtained in the form of radar images or radargrams have to be processed with the use of dedicated software and relevant filtration procedures. The selection of these procedures and their sequence is important and directly related to the aim of this study. The procedures and the order of their implementation were established based on [10] and [11].

3. Dielectric properties of concrete.

To be able to perform diagnostics studies with a georadar, it is necessary to have knowledge of basic electromagnetic properties of a given medium, i.e. particularly its magnetic permeability (μ), electric permittivity (ε) and conductivity (σ). This is a critical condition for the selection of filtration procedures.

Concrete, a porous, non-homogeneous material with pores partially filled with ionic solution, is essentially a low-loss non-magnetic medium. This implies that the magnetic permeability of concrete is $\mu_0 = 4\pi \times 10^{-7}$ H/m. The effective permittivity is expressed by the following formula:

$$\varepsilon_e = \varepsilon + \frac{\sigma}{j \cdot \omega} = (\varepsilon^I - j \cdot \varepsilon^{II}) + \frac{(\sigma^I + j \cdot \sigma^{II})}{j \cdot \varpi} = (\varepsilon^I + \frac{\sigma^{II}}{j \cdot \varpi}) - j \cdot (\varepsilon^{II} + \frac{\sigma^I}{\varpi}) = \varepsilon_e^I - j \cdot \varepsilon_e^{II} \tag{1}$$

where the real part of the effective permittivity ε_e^I containing ε^I and σ^{II} represents the ability of concrete to store electromagnetic energy. The imaginary part, which contains ε^{II} and σ^I expresses electromagnetic energy loss. The effective permittivity is usually divided by electrical permittivity in the air, which is $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m. The constant permittivity is defined as:

$$\varepsilon_r = \varepsilon_r^I - j \cdot \varepsilon_r^{II} \tag{2}$$

The real part ε_r^I is usually described as dielectric constant and expresses the amount of electromagnetic energy stored as electric polarization. The imaginary part ε_r^{II} (loss factor) represents energy losses induced by absorption and has a significant impact on the attenuation of waves. For concrete, $\varepsilon_r^{II} \approx 0$, owing to which constant permittivity is equal to dielectric constant. This makes the velocity of electromagnetic wave propagation depend solely on the dielectric constant [12].

Numerous studies have been devoted to the dielectric constant in concrete [13,14]. It has been found that:

- Moisture content has the most prominent effect on the value of dielectric constant.
- Relative permittivity and conductivity decrease with decreasing free water content in concrete.
- Differences resulting from the mix constituents or strength level have minor influence compared with the influence of moisture (except when steel fibres or honeycombing are present) on dielectric properties of concrete and affect conductivity more than permittivity.
- Resaturation produces similar permittivity and conductivity values to those obtained during drying.
- Temperature has a negligible effect on the velocity of electromagnetic wave in the concrete.

4. Measurement results

4.1. Apparatus

The pre-post-tensioned beams were examined using an IDS Alladdin impulse georadar with a 2 GHz bipolar antenna. Prior to the examination, the device was calibrated and the signal propagation velocity in the concrete medium was estimated to be within 8 to 10 cm/ns. The zones of increased moisture content were identified with a moisture meter. The penetration range was established to be about 0.5m.

4.2. Subject of study

The examination was performed on pre-post-tensioned beams manufactured by a precast concrete plant for the *in-situ* placement. The tensioning force was realized by preliminary deformation of active steel, i.e., cable, strands and bars. The tensioning progressed in two stages before and after grouting, when the concrete attained the required design strength.

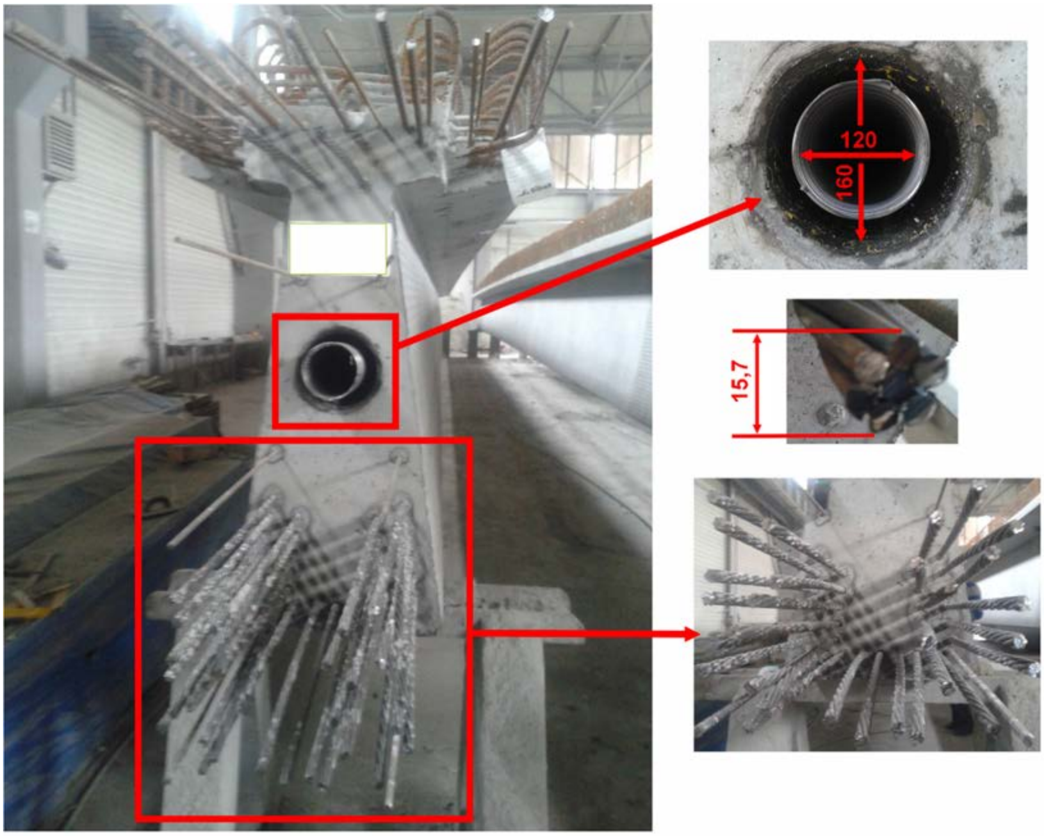

Fig. 2. Pre-post-tensioned beam manufactured at a precast concrete plant.

Each beam had protruding stirrups to cooperate with the concrete overlay. The cable trajectory agreed with the shape of the bending moments distribution. The lower prestressed reinforcement comprised seven reinforcement rows, with seven strands placed in the first row, two strands in the last row and four strands in the remaining rows. In the shear zones, wire looms were used to exclude the strands from interaction with the section. All the beams were made from C50/60 concrete, and the strands were 7-wire strands.

4.3. Measurement route

Each case of georadar profiling was performed from the bottom of the beam along its axis of symmetry. The travel routes of the device and beam sections are shown below.

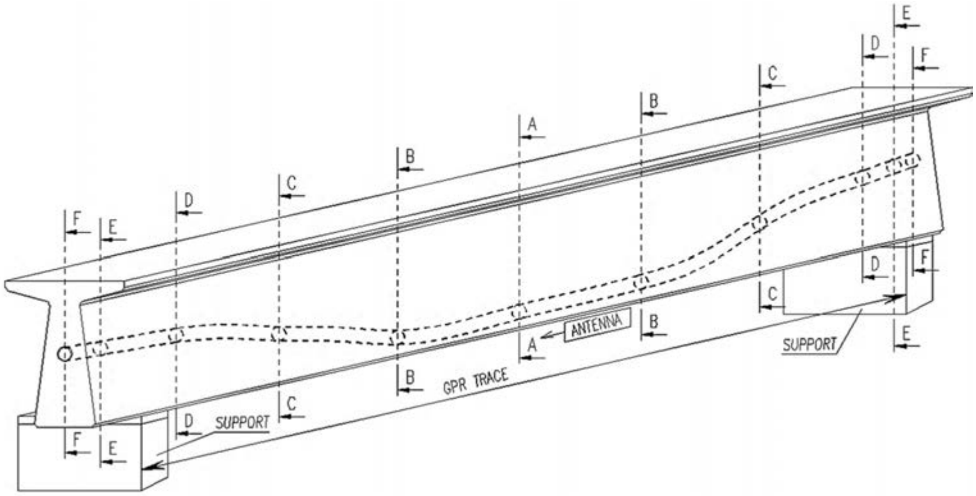

Fig. 3.Antenna travel route.

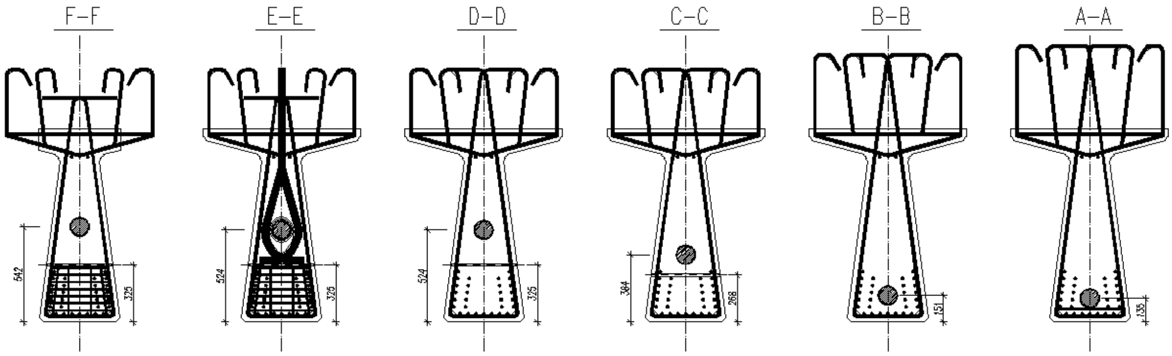

Fig. 4. Sections of the beam

The travel route of the georadar covered sections A-A, B-B, C-C and D-D. Sections E-E and F-F were inaccessible for scanning. The welded steel crossbars allowed establishing proper cable trajectory and securing it while casting.

4.4. Results

The examinations were performed on 30 pre-post-tensioned beams in the precast concrete plant. Przybliżony czas badania elementu od momentu profilowania do uzyskania raptortu końcowego wynosił około 12 godzin. Estimated time of the study, from profiling to obtaining the final report, was about 12 hours for a single beam. Each result obtained as a radargram was processed through filtering with the use of filtration procedures in the following order:

- Move start time
- Background removal
- Vertical bandpass filter (TD)
- Smoothed gain

A deformed cable duct was detected in one of the beams, as shown in the radargram for this anomaly below.

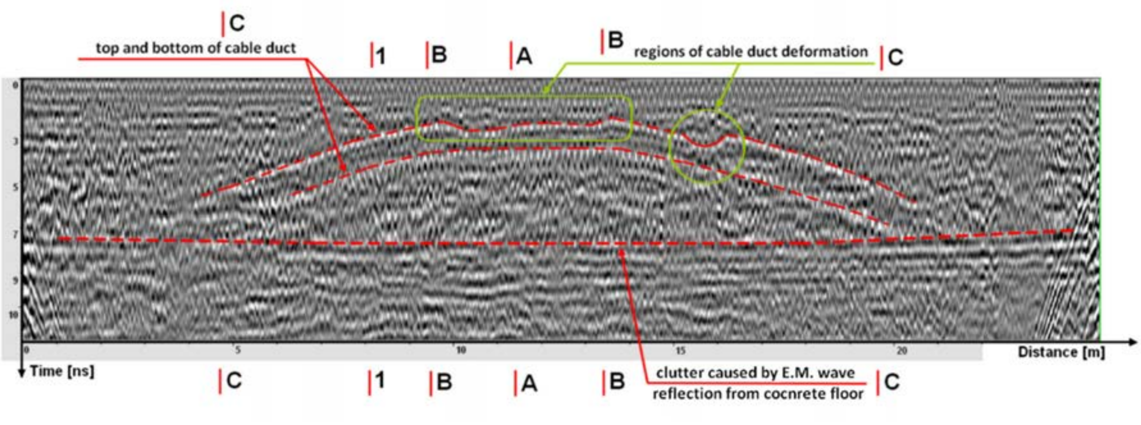

Fig. 5. Radargram of the deformed cable duct.

The radargram shows two zones in which the bottom part of the cable duct was deformed due to the highest concrete mixture pressure. These regions were examined with a moisture meter to make sure that the anomalies were not caused by the change in the signal propagation velocity resulting from the free water content variations. The device showed similar values, from 8.6 to 8.8%, in each beam region. The upper part of the duct was aligned in accordance with the designed route. Sections corresponding to the beam sections were detected and described. The interface running along the length of the beam represents the clutter caused by the electromagnetic wave reflections from the concrete floor. The wave image helps determine the spacing and number of stirrups, with the distance between the stirrups noticeably denser in the shear zone than in the span zone.

Because steel is an electric current conductor, a 100% of energy reaching this medium is reflected, which means that its conductivity is high and permittivity is low. This implies that in the case of two or more rows of reinforcement, the electromagnetic wave is reflected multiple times and the effective attenuation surface is reduced thus leading to the drop in the electric field intensity. Increasing the number of reinforcement rows by at least one row contributes to the lowering of the electric field intensity by at least 25% [15]. It is thus very difficult to determine the position of reinforcement using the radar method in the case of several rows of reinforcement.

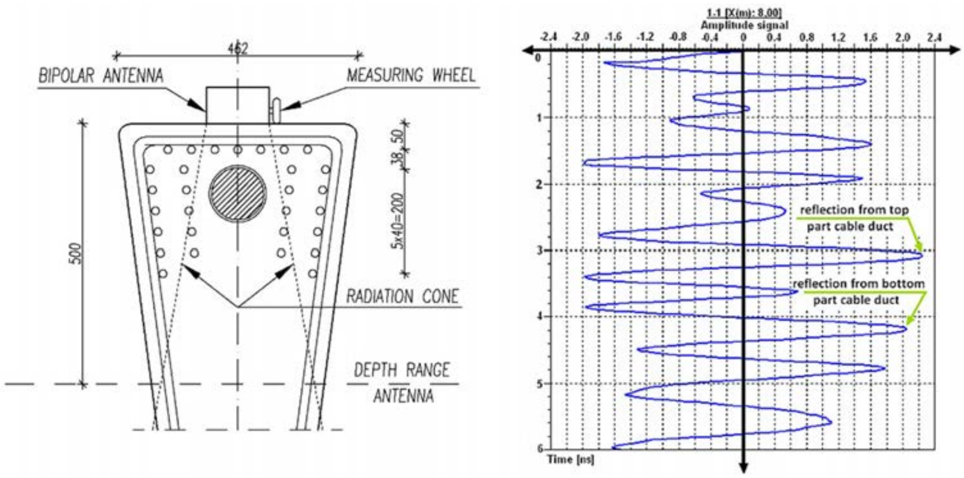

Fig. 6. Antenna radiation cone and signal distribution in section 1-1

Another important aspect is which reinforcement part is covered by the radiation cone. Figure 6 shows the portion of the strands captured by the cone and the distribution of signal in section 1-1. It can be seen from the figure that the cone covers the first, fifth and sixth row of strands. With this profiling mode, it is impossible to establish the position of the remaining rows. Based on the signal amplitude, it is possible to exactly define the time at which reflection from the lower and upper part of the cable duct occurred, as shown Fig.6. This allows locating the cable duct in the beam, as by determining the velocity based on the dielectric constant, we are able to calculate the route travelled by the signal.

Section D-D was not located on the radargram because the duct was beyond the range of the antenna and because of the number of reflection from the strand rows located below the duct, which deformed the propagating signal considerably and the image was impossible to interpret.

The quality of the lower cover can be evaluated based on the vertices of parabolas. Here, the vertices are arranged along one line, which confirms proper execution of the cover layer.

5. Conclusions

The examinations allowed capturing irregularities in execution of the pre-post-tensioned concrete beam. In this case, it was the deformation of the cable duct. It is a very important opportunity, as after the cable duct injection, it will be very difficult or even impossible to do it. Proper injection is critical from the perspective of structural safety because it provides the tendons with protection against corrosion and allows cooperation of the prestressed reinforced concrete section [16]. Random drillings to the duct near the mid-span of the beam after injection on a building site demonstrated this irregularity captured by the georadar. The injection in this zone was performed improperly.

The causes of the defect may include too large a distance between the fixing crossbars, missing crossbars or improper fixing. This might induce the deforming pressure of the mixture on the bottom part of the cable duct. The diagram is shown below.

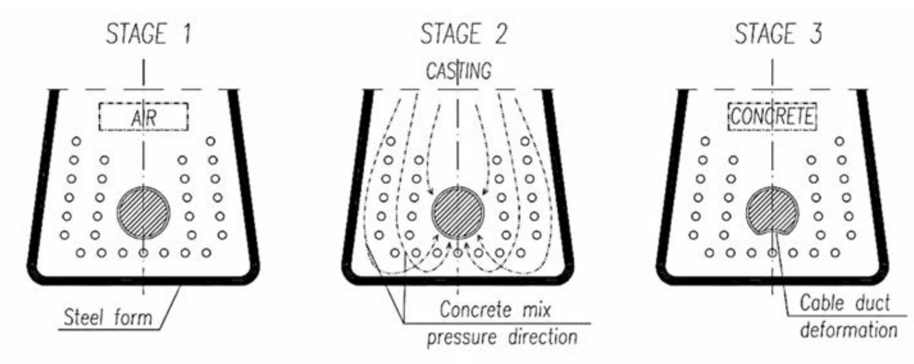

Fig. 7. Stages of cable duct deformation

The studies performed indicate that the radar method can be a source of valuable information for the assessment of pre-post-tensioned beam manufacture in the precast concrete plants. It has to be remembered, however, that the methods has some limitations resulting from the selection of apparatus, complexity of wave distribution in the case of several reinforcement rows, or radiation cone, which in the beams with complex geometry may not be able to cover the whole section of the beam. Proper interpretation and filtration of data obtained from the radar is also very important.

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