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Abstract

Maintenance costs of concrete structures can be reduced by efficient and extensive condition assessment. Rapid technological development has allowed application of innovative methodologies for the inspection of structures, which has in turn increased precision and efficiency of inspection activities. Potential for using ground-penetrating radar in the assessment of concrete structures has been considered for a long time and, with the improvement of the analysis tools, its application has been constantly increasing. Ground-penetrating radar is a technique based on emission of electromagnetic waves into the material, and on analysis of reflected waves, resulting in information about location and properties of a particular object. GPR is used for assessing condition of concrete structures, i.e. for the localization of reinforcement, determination of concrete cover, and localization of delamination. Recent research has shown that GPR data could be used for assessing corrosion of reinforcement. Following literature results on GPR-based study of concrete condition, main principles of GPR use are outlined in the paper.

Key words: ground-penetrating radar, condition assessment of concrete structures, corrosion of reinforcement

Primjena georadara u ocjeni stanja betonskih konstrukcija

Sažetak

Provođenje pravovremene, učinkovite i sveobuhvatne ocjene stanja građevinskih konstrukcija može utjecati na niže troškove održavanja konstrukcije. Ubrzani tehnološki razvoj omogućuje primjenu inovativnih metodologija u ocjeni stanja konstrukcija, što zauzvrat osigurava preciznost i učinkovitost inspekcije. Potencijal georadara u ispitivanju betonskih konstrukcija istražuje se već duže vrijeme, a od tada njegova primjena u raznim vrstama ispitivanja raste, uz kontinuirano poboljšanje analize rezultata. Georadar je uređaj čiji se rad temelji na emisiji elektromagnetskih valova u materijal nakon čega analiza reflektiranih valova daje željene podatke o položaju i karakteristikama objekta od koji se val reflektirao. U svrhu ispitivanja betonskih konstrukcija, georadar se koristi za lociranje armature, određivanje debljine zaštitnog sloja i pronalaženje delaminacija. Istraživanja su pokazala da se podaci prikupljeni georadarom mogu koristiti za procjenu korozije armature. U ovom radu predstavljen je osnovni princip rada georadara, nakon čega su predstavljeni rezultati istraživanja iz dostupne literature ocjene stanja betona pomoću georadara.

Ključne riječi: georadar, ocjena stanja betonskih konstrukcija, korozija armature

1 Introduction

Condition assessment is an important part of maintenance of concrete structures as it can efficiently minimise consequences of their degradation. Damage caused by degradation process is primarily assessed by visual inspection, during which defects such as cracking, rust staining, or water leakage, can be detected [1]. However, visual signs can in most cases be detected at an advanced phase of deterioration process only. Early detection of deterioration is therefore important for extending service life of concrete structures. Non-destructive methods have an important role in assessing condition of concrete structures. Main advantages of these methods over destructive testing methods are lower costs, reduced testing time, and no physical damage to structures [2, 3].

Ground-penetrating radar (GPR) is a technique initially designed for military use to locate buried objects [1]. With improvement of this device, the field of its application has expanded to various disciplines, including civil engineering, hydrogeology, archaeology, etc. [4, 5]. In civil engineering, GPR has been used in numerous applications as a non-destructive technique. For instance, it is used for localization of reinforcement, tendon duct mapping, localization of delamination, detection of voids, and determination of concrete cover thickness [1, 4, 6, 7]. Combined with other non-destructive methods, it enables faster and more efficient evaluation of the condition of concrete structures [8, 9]. Several investigations have shown that GPR data could be used for identifying corrosion of steel in reinforced concrete specimens [1, 7, 10–12]. This novel approach for the evaluation of corrosion could prove to be quite convenient because it does not require any connection to reinforcement.

This paper is organized in two parts. Fundamental design of GPR, and an overview of main effects influencing propagation of GPR signal, are presented in the first part. The second part offers a review of experimental investigations conducted so far for assessing condition via GPR measurements.

2 Ground-Penetrating Radar (GPR)

2.1 GPR setup

Ground-penetrating radar is designed to emit via transmitter electromagnetic waves into the material, and the waves are then reflected by the target and detected by the receiver, as shown in Figure 1 [4].

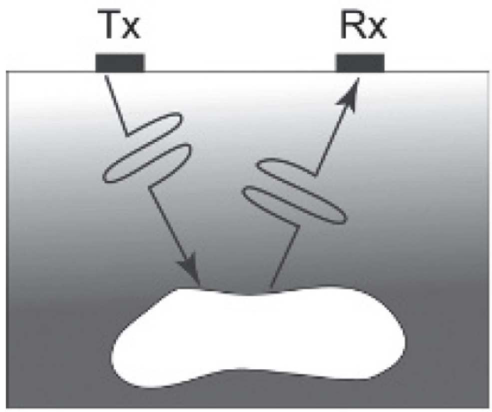

Figure 1. Ground-Penetrating Radar principle [4]

The depth of wave penetration is influenced by the antenna frequency. High-frequency antennas can detect objects with high resolution, but their penetration depth is smaller. On the other hand, radars with low frequency transmit waves to greater depths, albeit to the detriment of resolution [1, 13]. Their utilization for the detection of smaller defects in concrete is therefore questionable.

The reflection of an electromagnetic wave occurs at the interface between two different materials or, more precisely, at points where there is a difference in dielectric properties. The strength of the reflected wave depends on the contrast between dielectric constants of the materials; greater contrast means that the absolute value of the reflected wave amplitude will be higher. The reflection intensity can be described with the reflection coefficient, r:

$$\mathbf{r} = \frac{\sqrt{\varepsilon_{R_1}} - \sqrt{\varepsilon_{R_2}}}{\sqrt{\varepsilon_{R_1}} + \sqrt{\varepsilon_{R_2}}}$$

where ε_{R1} and ε_{R2} are relative dielectric constants of the upper and lower material [3]. The fact that steel is an almost perfect reflector [14] is used for locating reinforcement in concrete structures.

The results of GPR survey are usually presented in form of the A-scan, B-scan or radargram, and C-scan [1]. The A-scan or trace is a one-dimensional representation of wave propagation through the medium (Figure 2b). Time measurement is given on the horizontal axis and wave amplitude is recorded on the vertical axis. For a ground-coupled antenna, when a wave is emitted, the receiver first records a direct wave that propagates through the air from the transmitter to the receiver. Then a part of the electromagnetic wave is reflected at the surface of the material. These two components are called the direct wave (DW). The rest of the wave energy penetrates through the material until it reaches the material with different dielectric properties. The electromagnetic wave then reflects, and the receiver records it as a reflected wave (RW) (Figure 2).

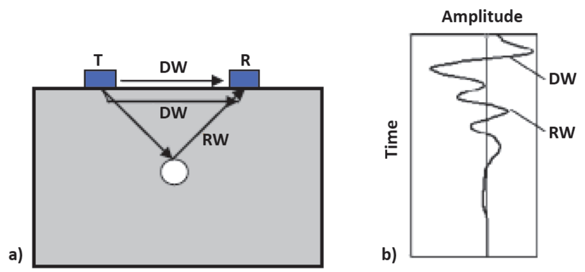

Figure 2. a) Paths of GPR signal; b) A-scan [1]

When antennas are moved in one direction, GPR data can be given as a B-scan or radargram (Figure 3a). If a survey is carried out in two directions, which is usually done by making a grid, a three-dimensional representation can be obtained (Figure 3b).

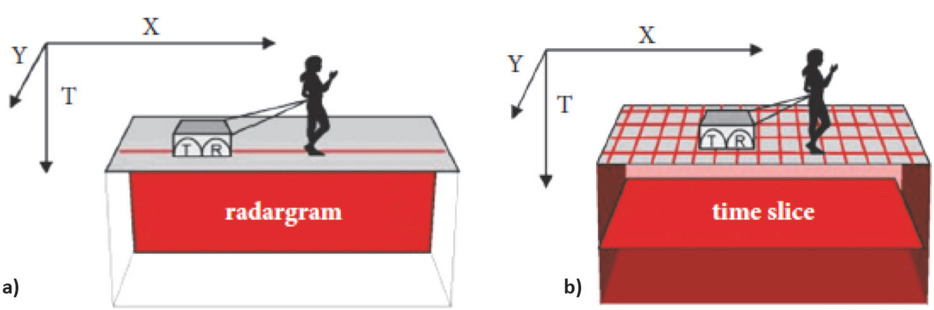

Figure 3. a) B-scan or radargram; b) C-scan [11]

If the reflected wave travel time from the transmitter to the receiver is known, and if the velocity of the wave, depending on dielectric properties of the material, is also known, then the depth of the object can be estimated.

2.2 Propagation of electromagnetic waves

The energy of electromagnetic waves reduces during their propagation, which is firstly caused by geometrical propagation of waves and, secondly, because waves travel through material [13]. The exposure of concrete to an electromagnetic field causes changes on the microscopic level [15], which results in wave attenuation. The attenuation depends on dielectric properties of the material, permittivity and conductivity, and these properties are highly influenced by moisture content and content of chloride ions dissolved in concrete pores [1, 13]. An increase in the moisture and chloride content causes an increase in dielectric properties of concrete [16] and decrease in the reflected wave amplitude.

3 Condition assessment using GPR data

Previous research [1, 7, 10–12, 17] has revealed that GPR data can be utilized for the assessment of reinforcement corrosion, as well as for the estimation of moisture and chloride content. The research performed so far shows that changes in travel time, wave amplitudes and frequencies, as derived from A-scans, can reveal deterioration processes in concrete structures, and also locate corroded areas within reinforcement.

3.1 Corrosion of reinforcement

Corrosion of steel in concrete is an electrochemical mechanism [18] that can be manifested in concrete structures in various forms. The most common forms of corrosion in concrete are general corrosion and pitting corrosion [19]. General corrosion is induced by decrease in pH value of concrete caused by carbonation of concrete or chloride penetration through concrete cover, which leads to degradation of the passive film of steel [18, 19]. Pitting corrosion happens when the passive film of steel is locally destroyed, usually induced by high chloride contamination from seawater and deicing salts [19]. The reinforcement surface devoid of passive film is a convenient environment for the occurrence of corrosion. The volume of corrosion products is higher than that of pure iron [19] and it results in the appearance of cracks. The formation of corrosion products at the interface between concrete and reinforcement causes amplitude change of the reflected wave, and this change can be noted with GPR [7]. Traditional method for assessing corrosion risk is the half-cell potential (HCP) method [18], but its main drawback is the necessity to make connection with the rebar. Therefore, some current investigations are aimed at replacing the HCP method with GPR.

3.2 Effect of moisture and chloride content on GPR data

Sbartai et al. [17] emphasized the influence of water and chloride content in concrete on GPR data. Their research pointed to the dominant influence of moisture content on the attenuation of direct and reflected waves. The increased chloride content caused further wave attenuation, and reflected waves showed higher sensitivity than direct waves. Research performed by Hong [1] confirmed that an increased moisture content causes delayed travel time of reflected waves, and decrease in amplitude and peak frequency of direct and reflected waves. This is closely related to the dielectric permittivity of concrete and the velocity of the GPR signal, leading to greater attenuation. In experimental examination [10] where different exposure conditions were simulated by immersing corroded rebars in three different water oil emulsions, the emulsions with higher dielectric permittivity ensured an increase in travel time of reflected waves and decrease in amplitude. Similar observations about the relation between dielectric permittivity and signal attributes were made by other authors [7, 20].

3.3 Effect of reinforcement corrosion on GPR data

One of the first studies to have acknowledged GPR potential for corrosion detection was published by Hubbard et al. in 2003 [12]. Their results show that corrosion influences decrease in spectral amplitude. However, the authors point to the significance of the effect of moisture on the GPR wave behaviour. However, the authors point to the significance of the effect of moisture on the GPR wave behaviour which is not excluded in this experiment. Hong [1] showed that the advancement of corrosion process is related to the growth in amplitudes of reflected waves and decrease in travel time. This was also concluded in [7], and this phenomenon was attributed to the presence of corrosion products in concrete cover. Corrosion products made larger interfaces (corrosion products, concrete, steel, cracks) which affected reflected waves. The increase in wave amplitude with corrosion progress is also revealed in [21, 22]. On the contrary, lower amplitude in corrosion process, resulting from increased chloride content and presence of corrosion products, is reported in [11]. It seems that in this paper the influence of corrosion products is not clearly distinguished from the effect of chlorides in wave reflection and, consequently, the results can only be attributed to the concurrent action of both effects.

3.4 Corrosion assessment in-situ

The above mentioned studies were performed in controlled laboratory conditions where different parameters can be controlled. However, it is hard to perceive corrosion in-situ without raised moisture or chloride content. Therefore, various approaches have been applied to assess condition of concrete structures, and in many of them attempts have been made to predict probability of corrosion according to the areas with high attenuation, caused by high moisture and chloride content [23]. Special efforts have been made to establish a relation between results obtained with HCP and GPR methods. In [24], a comparison was made at nine bridge decks between GPR signal attenuation areas and results acquired by the half-cell potential method. The attenuation was used to predict deteriorated areas and a good agreement was established between these two methods. Regardless of concrete condition, the amplitude attenuation depends on concrete cover, and so Barnes et al. [23] revealed the depth correction for the reflected amplitude, and the resulted amplitude was then correlated only with dielectric properties of concrete cover. Martino et al. [25] went a step further and used the ROC (Receiver Operating Characteristic) curve to determine the threshold value for the rebar reflection amplitude, which distinguishes corroded from healthy areas, and a high accuracy between HCP and GPR method was established. Also, the attenuation of the GPR signal was used to monitor the progress of deterioration at the concrete bridge deck by comparing results from various surveys conducted over two years [26]. The attenuation map was compared with the map of electrical resistivity of concrete, and the authors attributed strong correlation between these methods to the fact that both of them are primarily subordinated to the electrical conductivity of concrete. Besides, the GPR results were used for assessing the overall condition of concrete decks by calculating the GPR condition index (CI), which is the indicator of the level of deterioration [27]. It can be combined with other condition indices obtained with other NDE methodologies for assessing condition of bridge decks [28]. As an example, the GPR condition map obtained with the robotic survey is shown below.

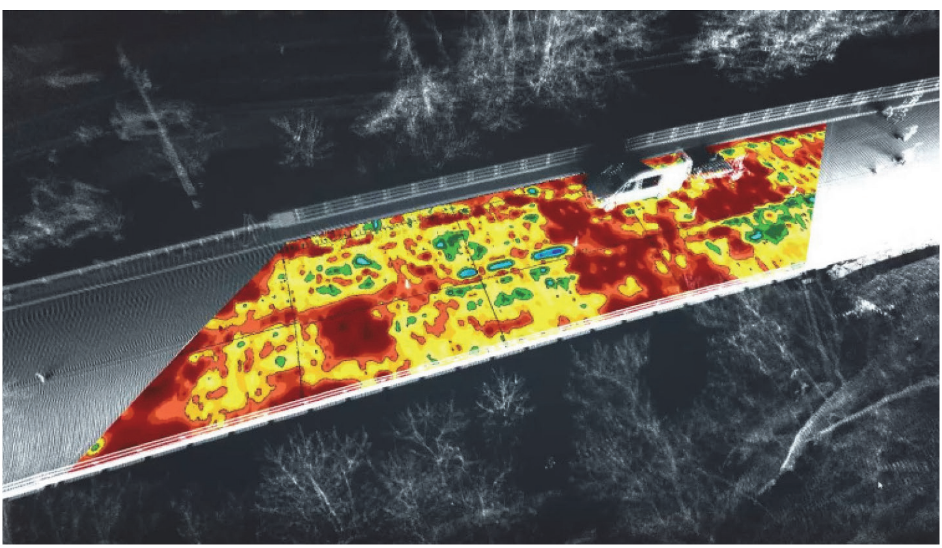

Figure 4. GPR condition map [28]

4 Conclusion

Based on the above-presented brief review of previous studies, where observations about the relationship between the GPR data and condition of concrete are given, the following conclusions can be made:

- The presence of moisture and chlorides in concrete induces wave attenuation and time delay, and is caused by the changes in dielectric properties.
- The review of laboratory examinations, where the effect of corrosion was considered, does not clearly highlight the effect of corrosion on wave amplitude; some authors argue that corrosion results in a decrease in amplitude of reflected wave because of higher permittivity of concrete cover contaminated by corrosion products, while others identify the higher interface between concrete and rust with stronger wave reflection. However, it is difficult to fully compare results of various examinations because reinforcement corrosion has been accelerated by different methods.
- The attenuation of GPR signal is a possible sign of deterioration of an existing concrete structure.

As a non-destructive method, GPR could be very useful for condition assessment of concrete structures thanks to its mobility and efficiency. Nevertheless, it has some limitations. GPR data cannot provide information on corrosion stage; the attenuation of GPR signal can only point to the possibility of corrosion. Overall, its most suitable application would be for monitoring concrete structures. Variations between consecutive surveys could reveal the progress of deterioration process. In such a way, combined with the engineer's experience, the early detection of corrosion could be possible. Despite this, appropriate analysis and presentation of GPR data are not possible without deep understanding of its complexity. It is evident that GPR data are dependent on many factors, moisture and chlorides, stage of corrosion, rebar depth, surface roughness, etc. Thus, every influencing factor must be considered to provide for a reliable interpretation of the GPR signal and make claims about condition of structures.

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