GPR Image Analysis for Corrosion Mapping in Concrete Slabs

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Abstract: The ground penetrating radar (GPR) has been considered for a long time as a potential nondestructive evaluation (NDE) technique for assessing condition of concrete slabs. Unfortunately, despite many advancements with respect to the hardware configuration, this technology is still of limited practice due to the limitation of current data analysis methods. Recently, a new data evaluation approach has been proposed. This approach is based on visual analysis of GPR profiles in order to interpret and map the condition of concrete slabs. Since the description of this method is not well documented and its accuracy has not been verified, the main aim of current research is to study and investigate these topics. While the research is on-going, this paper reports its initial result. Specifically, the paper presents a detailed procedure to assess and map GPR data of concrete slabs using image analysis. In addition, the limitations of current GPR data evaluation methods are also discussed.

1 Introduction

The condition assessment of concrete slabs provides required inputs for programming slab maintenance activities. In Canada and the United States, the main approach to evaluate condition of a slab, as for other structures, is based on visual inspection. Although this approach is effective in finding external defects such as cracks, scaling and spalls; it cannot to detect subsurface flaws such as voids, internal cracks, delaminations, or rebar corrosion. This problem is especially more obvious for paved structures.

To overcome the limitations of visual inspection, various nondestructive evaluation (NDE) technologies have been studied by both the industry and research community. Among these technologies, the Ground Penetrating Radar (GPR) has been considered for many years as a highly potential technique. However, despite the fact that many advancements regarding the hardware configuration have been made, the technology is still of limited practice. The main reason, revealed by review of the literature as well as discussion with transportation agencies, is that the technique has not provided consistently accurate results.

Given the situation, a research project has been granted by the Ministry of Transportation of Quebec (MTQ) to a joint research group formed between Concordia University and Radex Detection Inc. The objective of this research is to enhance the performance of GPR technology as a tool for condition assessment of concrete bridge decks. At the beginning, the group has recognized that the successful application of a nondestructive technology to structure condition assessment depend upon two important factors, namely (1) hardware capability and (2) data analysis technique. Since the main shortcomings are currently due to data analysis, not to GPR equipment (Saint-Pierre 2010; Tarussov et al. 2013), data evaluation is the focus of this research.

2 Research Objective and Methodology

The ultimate goal of this research is to study and assess the visual method for analyzing GPR data of concrete slabs. The method is expected to enhance the inspection performance of the GPR technology. In order to achieve that goal, the overall research process is divided into the following steps:

(i) Study the background and technology

(ii) Identify and study available analysis approaches for GPR data.

(iii) Develop a detailed procedure for GPR data evaluation technique using image analysis

3 Background and Literature Review

3.1 Deterioration of Concrete Structures

The need of inspection comes naturally because of deterioration of concrete structures. It is known that the deterioration of concrete structures is a result of combined effects of many complex phenomena. Penttala (2009) classifies two broad mechanisms of reinforced concrete bridge deterioration, namely, physically-induced and chemically-induced processes. Specifically, he defines physically-induced deteriorations are those processes caused by factors such as freeze-thaw loads, non-uniform volume changes, temperature gradients, abrasion, erosion and cavitation while chemically-induced deteriorations happen because of carbonation, chloride ion, sulfate and acid attacks or alkali-aggregate reactions. With such a variety of mechanisms, deterioration of most concrete bridges in North America, however, is associated with corrosion of reinforcing steel bars that caused by de-icing salt applied on bridges during winter or by salt in seawater for structures built in marine environments (Qian 2004). In US alone, approximate 20 percent of the cost to rehabilitate its bridges is attributed to chloride-induced corrosion (Al-Qadi et al. 1993).

Although the exact mechanism is not known, it is observed that when the presence of chloride reaches a certain extent, it breaks down the passive oxide film and the condition is ready for corrosion to be initiated (Carino 2004). The reinforcement corrosion then happens because many tiny electrolytic cells are formed. In these cells, the water in the pores of the paste contains various dissolved ions and serves as the electrolyte while heterogeneities in the surface of the steel cause some regions of the bars to act as the anodes and other regions to act as the cathodes. Since the rusts, product of corrosion, occupy much bigger volume than the original steel, they produce internal stresses and causes internal cracks in the concrete structure. These internal cracks are usually mistermed as “delaminations”. At the beginning, the delaminations usually have a small size and locate separately. Once growing up and encountering one another, they become a spall that can be visually observed.

3.2 The Ground Penetrating Radar (GPR)

The ground penetrating radar (GPR) is a detection technique that came to civil engineering application from the geophysics discipline. This technology detects subsurface objects or defects based on the principle of electromagnetic (EM) wave propagation. Specifically, when a beam of EM energy encounters an interface between two media of different dielectric constants, a portion of energy is reflected back while the remainder penetrates through the interface into the second medium. This working principle is illustrated in Figure 1. The intensity of reflected energy is dependent upon the intensity of incident energy at the interface and the relative dielectric constants of the two media.

For inspection of a structure such as a bridge deck, or a parking garage slab, an antenna is dragged manually on a pushing cart by an operator, or attached to a vehicle, in order to scan over the inspected surface. This antenna transmits brief pulses of electromagnetic energy into the surveyed structure. The energy reflected at various medium interfaces is then received by the antenna to produce the output signal. Since the process is repeated at a certain frequency, when the antenna is moved along the survey path, it produces a two-dimensional GPR profile. A typical GPR profile for concrete slab is shown in Figure 2. As can be seen, including a huge number of individual GPR signals, this profile contains a lot of information regarding structural condition.

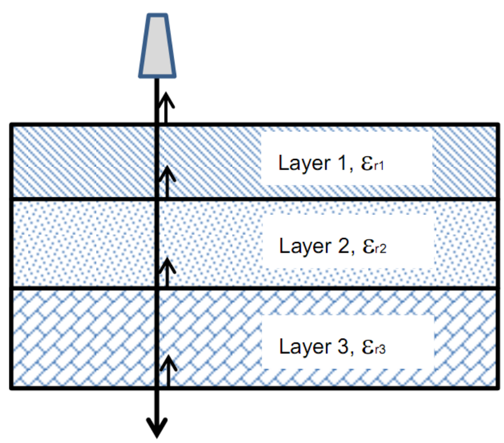

Figure 1 Principle of Ground Penetrating Radar (GPR)

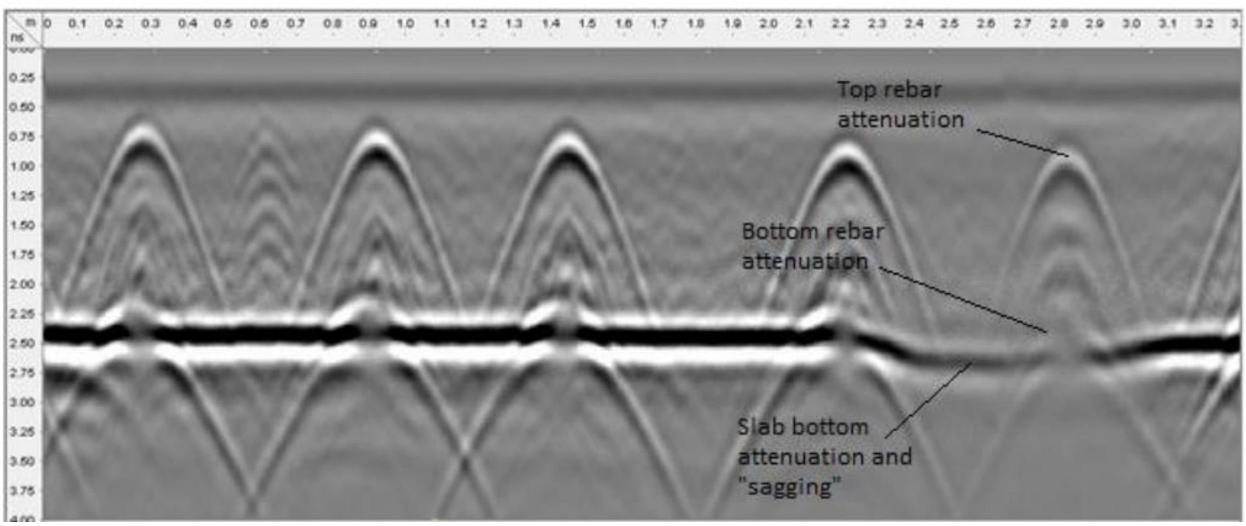

Figure 2 A GPR profile for concrete slab showing a corrosion anomaly between 2.4 and 3.0m

Numerous research projects have been carried out to investigate GPR technology for condition assessment of concrete structures in many of which focused on studying GPR data interpretation. Basically, the analysis methods proposed by these researches fall into either one of the two categories, namely (1) numerical analysis and (2) visual (qualitative) interpretation. Different aspects of numeric analysis have been discussed in a large number of publications, while very few sources address visual analysis of GPR data. The reasons for more accurate results delivered by visual analysis are outlined in Tarussov et al. (2013), however no specific explanation of the analysis technique is given. There is also little statistical proof of the visual concept. Each data analysis method will be discussed in the next sections.

3.3 Numerical Analysis

Numerical analysis is a technique for analyzing GPR data based on the measured amplitudes of various medium interface reflections. Currently, it is the most commonly used technique for evaluating GPR data of concrete slabs. Using this method, the analyst will infer the concrete slab condition based on the normalized reflection amplitude at the concrete surface, slab bottom or top mat transverse reinforcing bar (ASTM 6087; Maser 1995,1996; Maser and Bernhardt 2000; Parrillo et al. 2006) . The rationale behind this evaluation is the known effect of moisture, chloride content and rust on the recorded GPR signals. The presence of these substances increases the dielectric constant and electrical conductivity of concrete.

Numerical processing, however, has provided results with inconsistent accuracy (Barnes et al. 2008). The reasons pointed out are the subjective selection of the threshold value of amplitude measurement to define the existence of corrosion damage, and the variation of rebar depth caused by imperfect construction. Tarussov et al. (2013) pointed out some more factors that lead to this inefficiency such as reinforcing bar spacing, surface properties, other structural variation, and so on.

Some efforts have been made to solve the above problem of numerical analysis approach. For example, Barnes et al. (2008) proposed a statistical technique to account for signal depth – amplitude effects. Dinh and Zayed (2013) developed a correlation-based method to account for above-mentioned impact factors. However, the limitation of their method is that it requires the original GPR signals or profiles acquired soon after construction of the deck. Currently, these data are not available for most structures in question.

3.4 Visual Interpretation

Graphical analysis refers to those techniques that are based on operator's experience and understanding of the structure to visually interpret GPR signals. The idea is not new: Chung et al. (1992) developed a technique for asphalt-covered reinforced concrete bridge deck evaluation using this approach to analyze individual waveforms collected with an elevated (horn) antenna. The method is based on the characteristic "W- shape" of GPR signals in which any variation from this W-shape characteristic is considered indicating some signs of deterioration.

Also based on that idea, Barnes and Trottier (2004) implemented a study to investigate the effectiveness of GPR for forecasting repair quantities of concrete bridge decks. The research reported a varying range of forecast accuracy. Specifically, the method seems to work well when the decks exhibiting deterioration levels between 10 and 50%. For the decks surveyed that contain less than 10% and more than 50% deterioration of the total deck surface area, the results shown significant differences between the GPR and ground-truth survey quantities.

Based on visual interpretation, Tarussov et al. (2013) proposed a new method for interpreting GPR data of concrete structures, using line-scan image analysis. The interpreter scrolls through each GPR profile and then marks deteriorated regions, based on defined visual signs of deterioration. The processed profiles are then combined by a specialized software tool to generate a deterioration map.

As can be seen, the concept behind visual analysis method is intuitive and easy to understand. The detailed analysis procedure is developed and presented in the next section.

4 The Proposed Procedure

This section presents a systematic procedure for analyzing GPR data of concrete slabs based on image analysis. The purpose, as stated earlier, is to make visual analysis become a widely accepted data analysis method. The proposed workflow for GPR image analysis is shown on Figure 3. As can be seen, this approach consists of five main steps.

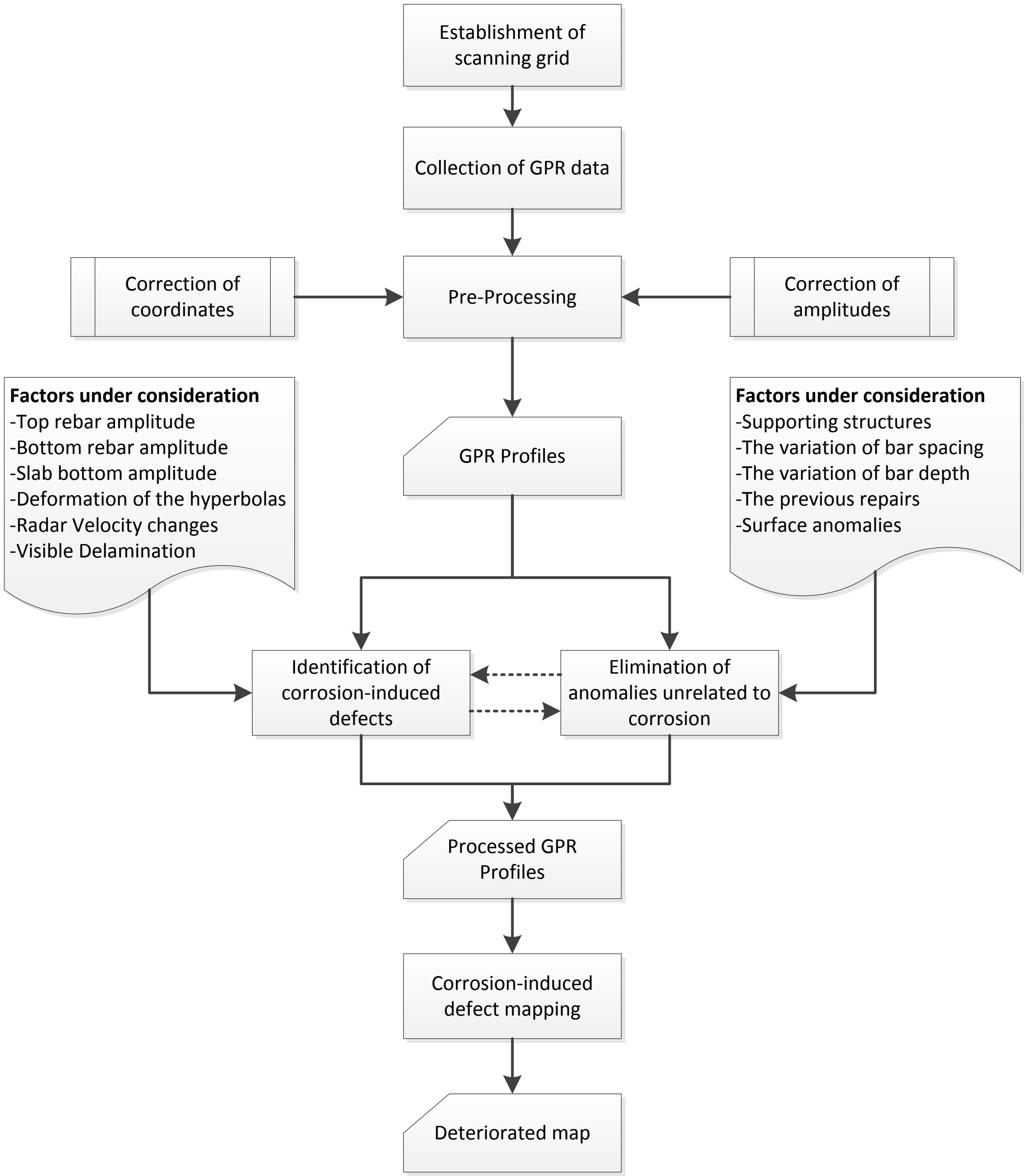

Figure 3 Workflow of Proposed GPR Data Analysis Method

Step 1 Establish scanning paths or grid

In this first step, the inspector needs to study, prepare the plan of the surveyed concrete slab. Then he needs to determine and mark the planned scanning paths or grid.

Step 2 Collect GPR data

Based on the scanning grid established in step 1, the inspector collect the GPR data for each scan line. The output of this step is a number of GPR profiles. Data collection for GPR image analysis is no different from the data collection for numeric analysis, except the requirement for recording data without differential gain that is unimportant for image analysis. Any data collected for numeric analysis can be used for visual image analysis.

Step 3 Data Pre-Processing of GPR profiles

In this step, each GPR profile will be processed before being ready for analysis and organized into a data grid. The purpose for doing this is to correct the coordinate and the amplitude. The output of this step is a two-dimensional grid of pre-processed GPR profiles. Unlike data used for numeric analysis, image analysis is performed on GPR profiles optimized for viewing, with appropriate differential gain applied.

Step 4 Identify corrosion-induced defects and eliminate anomalies unrelated to corrosion

In principle, there are two interrelated tasks in this step, including (1) Identify corrosion-induced defects and (2) to eliminate anomalies that are unrelated to rebar corrosion. Specifically, each GPR profile is analyzed and the regions associated with deteriorated areas are marked.

The identification of defects is based on the understanding of the inspected structure while considering the following parameters (see Fig. 2 above):

(1) Top rebar amplitude;

(2) Bottom rebar amplitude:

(3) Slab bottom amplitude;

(4) Deformation of the hyperbolas;

(5) Radar Velocity changes; and

(6) Visible Delamination.

These parameters are taken into account as the most indicative of slab condition.

As mentioned above, the factors that need to be considered for eliminating unrelated anomalies include:

(1) Supporting structures;

(2) The variation of rebar spacing;

(3) The variation of rebar depth;

(4) The previous repairs; and

(5) Surface anomalies.

These factors are main causes of error in numeric data analysis, but are easily recognized and eliminated in image analysis. For example, the effect of rebar placement to reflection amplitude can be seen in Figure. 4.

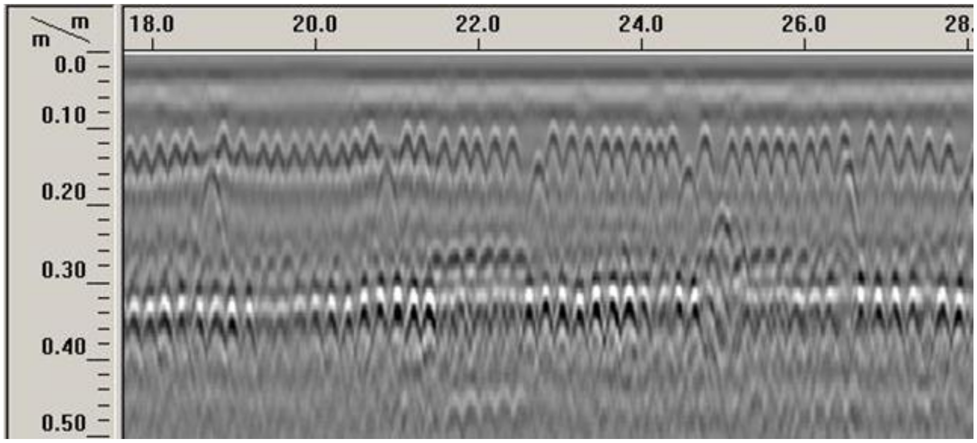

Figure 4 Apparent attenuation anomalies at the slab bottom, unrelated to concrete condition (19 to 20 m, 21 to 22.5 m, 25 to 26 m). These are caused by variations in rebar placement and can only be correctly interpreted by visual image analysis

Step 5 Mapping of deteriorated zones identified by GPR image analysis.

In this step, marked regions associated with each GPR profile from step 4 are mapped to the grid prepared in step 3. Then, a complete condition map of slab in question is produced by connecting the same region types from separate scan lines.

5 Case Study

The preliminary assessment of GPR image analysis is performed for an underground parking garage in Montreal. GPR scans were collected at 100 locations before destructive cores were taken. These GPR data were then analyzed visually using step 4 of the procedure described in this paper, and compared with core analysis results. In the figures below, position of the cores in the GPR profiles was identified by the dashed lines. Presence of corrosion was assessed separately for top and bottom reinforcement. Examples of this analysis are shown below in Figure 5, Figure 6 and Figure 7.

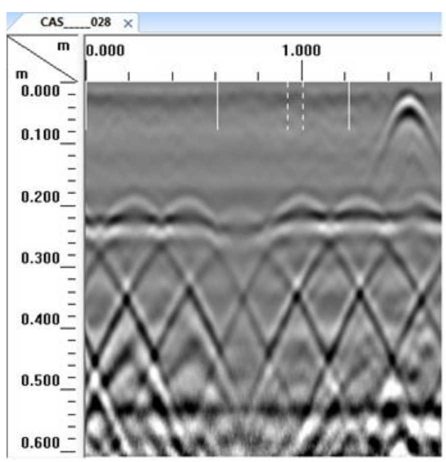

Figure 5 Core located just 200 mm outside a small corroded zone in good concrete (core position is marked with dashed lines). Core inspection shows no delamination or increased chloride content.

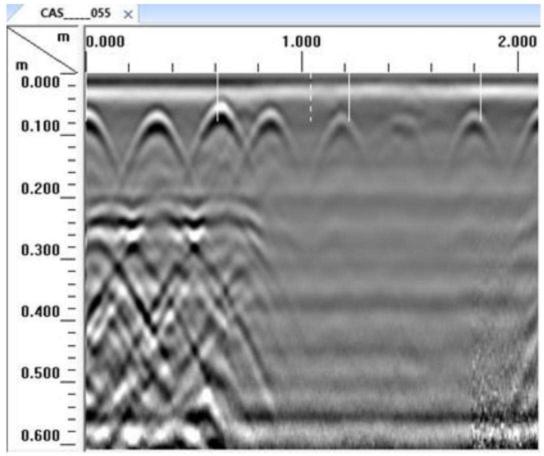

Figure 6 Core located within a severely corroded zone (dashed line), shows high chloride content but no delamination. GPR shows delamination further to the right, between 1.200 and 1.600 m.

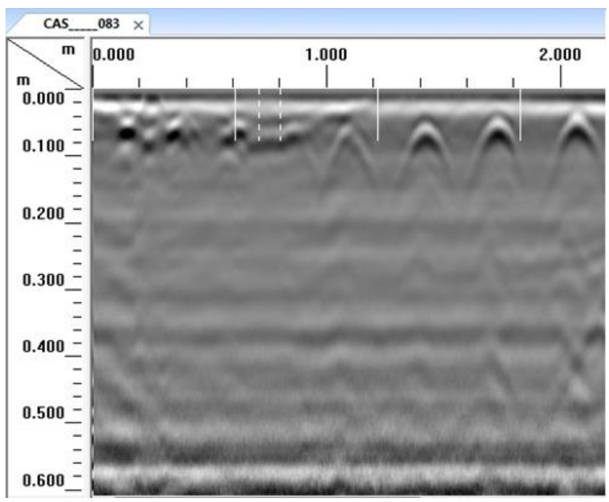

Figure 7 Inspection of the core located in a zone where corrosion and delamination are detected by GPR (dashed lines), shows delamination and extremely high chloride content (over 2000 ppm)

The comparison of a statistically significant series of 100 cores with corresponding GPR images demonstrates that GPR image analysis correctly identifies presence or absence of deterioration. It also detects the edge of deteriorated areas within a single rebar spacing. Among various types of deterioration, radar is most sensitive to the degree of rebar corrosion, which correlates well with the chloride concentration in cores. Delamination is always present wherever it is detected in GPR images, but the opposite is not true – delamination cracks, especially thin ones, may not show in GPR images. Therefore, GPR detection of corroded areas is more reliable than direct detection of delamination.

6 Discussion

Slow processing has been a major argument against visual analysis of GPR data. Therefore, in order to test performance of image analysis, another experiment has been carried out in which the software tool described in Tarussov et al. (2013) was used. In the experiment, a trained analyst was asked to process data for an average bridge deck (200x20 m surface). The result showed that the analyst can visually identify anomalies in 100 linear meters of GPR profile per minute which makes processing of a 1000 m long bridge in three to four hours possible. Once the defect identification is completed on the profiles, a deterioration map is generated within seconds. This is remarkably fast, compared to the reported times of up to three weeks required to numerically process a similar dataset. Preliminary assessment of GPR image analysis in the case study has shown a near-perfect correlation. Here the conditions are concerned with chloride content and presence of visible delamination. GPR image analysis has the ability of delineating zones affected by corrosion within a bar spacing, typically 200 to 300 mm. This is more accurate than any numeric amplitude analysis or corrosion potential maps. GPR image analysis owes its accuracy to the fact that the analyst uses several parameters to identify a corrosion anomaly. Reliable elimination of unrelated anomalies further increases the quality of results. Among various defects, GPR image analysis is most reliable for detecting presence of corrosion. Severe corrosion is in most cases associated with delamination, but direct detection of delamination is unreliable as small delamination cracks are invisible to GPR. A combination of rebar attenuation (weaker reflection amplitude), slab bottom attenuation and slab bottom sag (indicative of slower radar pulse velocity), is required to identify an anomaly as deterioration. Signal attenuation is caused by increased conductivity of concrete surrounding corroded rebar, while the decrease in radar pulse velocity is due to increased moisture in deteriorated areas.

7 Conclusion

GPR image analysis by a trained specialist is a highly effective method of concrete condition assessment. Simultaneous analysis of top and/or bottom rebar reflection amplitude, slab bottom reflection amplitude and shape as well as presence of visible delamination, is key to accurate identification of areas with rebar corrosion. Recognition of the anomalies unrelated to the condition of concrete, eliminates the inconsistency that characterizes numeric amplitude analysis of GPR data.

By eliminating the need for selective amplitude extraction (picking), GPR image analysis is several times faster than conventional numeric amplitude analysis. Visual identification of deteriorated zones is a quick and accurate process; the following mapping procedure is automated using a simple software tool.

GPR image analysis allows to delineate areas of rebar corrosion within a rebar spacing, typically less than 300 mm, which cannot be achieved with any other non-destructive method, including numeric GPR analysis, corrosion potential or chain drag. It is applicable to paved and unpaved slabs.

The next step to make GPR image analysis the accepted method of condition assessment, is to conduct tests followed by extensive destructive inspection, in order to provide a more accurate estimate of its accuracy and limitations.

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