Image-Based Versus Numerical Analyses of Concrete Bridge Decks using GPR

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Abstract  Ground Penetrating Radar (GPR), a commonly used non-destructive technique, shows high potential in condition assessment of concrete structures, such as bridge decks. The current method of interpreting GPR data is based upon numerical analysis, i.e. amplitude mapping (ASTM 6087), a method, which holds some major shortcomings reflected in the subjectivity in selecting the threshold values of amplitude measurements, inability to determine the degree of rebar corrosion, time spent in the analysis, and the amount of information lost during such analysis. Due to these factors, the resultant deterioration map from numerical amplitude analysis has lack of correlation with actual ground condition when compared at construction/demolition phase. Therefore, this research introduces the details of a recently developed corrosion mapping procedure based on visual image analysis of GPR profiles. A five phased methodology is presented to visually interpret GPR profiles/images. During the course of this research, GPR surveys have been carried out on several bridge decks and then verified against various sources of information on the actual decks’ conditions. Data are analyzed using numerical and visual-based image analysis methods for a case study in Montreal (highway 40). The results show the superiority of the proposed visual-based image analysis methodology in identifying subsurface anomalies and providing a defined probable corrosion maps. The constructed maps using the two methods are compared where the results are further validated through photos taken from the studied bridge. Photo analysis for the bottom side of the bridge deck show deterioration signs and patterns that coincide with GPR maps using image-based analysis.
1 Introduction

The Federal Highway Administration (FHWA) estimated 170 Billion US Dollars would be needed on an annual basis to significantly improve conditions and performance of highways [1]. Moreover, the Canadian Urban Transit Association (CUTA) echoed the same message at the federal level, that infrastructure needed a total of 53 Billion Canadian Dollars in 2013 [2]. The growing problem of infrastructure aging and deterioration in several countries has created needs for a further detailed inspection system that is able to sufficiently provide in-depth inputs for maintenance decision making and budget allocation.

In the United States and Canada, the condition assessment of concrete infrastructure is based generally on Visual Inspection (VI). Valuable information on the infrastructure condition could be obtained by VI. Nevertheless, the results are deemed qualitative and subjective to the knowledge and judgements of inspectors [3]. Deterioration is regularly a subsurface mechanism that starts internally and increases in severity before it spreads to reach the surface. Undetected subsurface flaws in addition to delayed maintenance may cause deterioration and eventually damage the structure. Therefore, maintaining the civil infrastructure forms a challenge associated with identifying the subsurface defects before the damage becomes too severe [4]. Various Non-Destructive Evaluation (NDE) techniques have been utilized in an effort to evaluate and quantify sub-surface defects. One of the common NDE technologies used is Ground Penetrating Radar (GPR) which has demonstrated high potential for condition assessment of concrete structures for over 30 years [5]. However, this technique remains of limited practice, because it didn’t steadily provide reliable results [6] and its main shortcomings lie in improper interpretation of GPR data rather than GPR hardware [6], [7].

Therefore, the objectives of the present research are: (1) Identify and study current practices of interpreting GPR data; (2) Present a detailed approach of evaluating GPR profiles using visual-based image interpretation; (3) Illustrate the various cases of signal attenuation, together with their causes in order to clarify the concept of image analysis technique.

2 Background

2.1. Ground Penetrating Radar

Ground penetrating radar (GPR) is an object-detection technique that is based on the propagation behavior of Electro Magnetic (EM) waves. 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 next medium. To inspect a structure, such as a pavement or a bridge deck, an antenna is dragged manually using a pushing cart or a moving vehicle. This antenna transmits short pulses of electromagnetic energy into the surveyed structure. Reflections of energy at various material interfaces are received by another antenna (bistatic mode), or sometimes by the same antenna (monostatic mode), to produce the output signal (A-scan) that is proportional to the amplitude of the reflected electromagnetic field. The output is usually presented as a grayscale image (GPR profile or B-scan).

2.2 Numerical Analysis of Reflection Amplitude

Numerical analysis of reflection amplitudes is the most commonly employed interpretation of GPR data, it is based on the measured amplitudes of various medium interface reflections. The dielectric constant and electrical conductivity of concrete will increase by the presence of moisture, chloride content and rust on the recorded GPR signals, thus the analyst can determine the concrete slab condition based on the normalized reflection amplitude at the concrete surface, slab bottom or top mat reinforcing bar.

Amplitude mapping consists of measuring reflection amplitudes at top mat rebar over the entire survey area and plotting them with contour lines. According to Parrillo et al. [8], however, the amount of deterioration should not be determined based solely on colors, on the contour map. He pointed out that even a new deck will contain some range in rebar reflection amplitudes due to rebar depth variation. For the same reason, Geophysical Survey Systems Inc. (GSSI) recommends that amplitude interpretation technique is not appropriate for a deck with no deterioration or a deck with near total deterioration [9]. Even for a bridge deck with average deterioration, in addition to rebar depth variation, there are still several factors that may lead to the inefficiency of analyzing reflection amplitudes [7]. These factors include the variation of rebar depth and rebar spacing, surface properties, structural configuration, and so on. Numerous researchers investigated the numerical analysis of GPR data of concrete bridge decks, examples can be found in [10], [11], [12], [13].

2.3 Image-Based Analysis of GPR Data

Image analysis method refers to the technique based on operator’s experience and understanding of the structure to visually interprets GPR signals. Based on visual analysis, Tarussov et al. [7] proposed a new method for interpreting GPR data of concrete structures using line-scan image analysis. This method requires an analyst
to scroll through each GPR profile and mark 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 inferred, the concept behind visual-based interpretation analysis is intuitive and easy to understand. Dinh et al. [6] followed the research by conducting a detailed procedure to assess and map GPR data for concrete slabs using image-based analysis. Moreover, Dinh and Zayed [14] used correlation analysis as a signal processing technique to compare individual GPR (A-scans) to interpret conditions of concrete bridge decks. This research defines the detailed steps for the initial method proposed by Tarussov et al. [7] where the visual interpretation procedure is further investigated and explained in details and later validated through a case study.

3 Research Methodology

The systematic procedure for visually interpreting GPR profiles for concrete structures is illustrated in Fig. 1 and presented through the following five steps:

**Step 1** Establish scanning paths or grid: After a comprehensive study of the area to be scanned, the inspector prepares a plan on which he determines the scanning paths or grid.

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**Fig. 1. Methodology Flowchart**
Step 2 Collect GPR data: At this stage, the inspector starts scanning each path determined from the previous step to collect data (GPR profiles).

Step 3 Pre-processing of GPR data: Each GPR profile is processed and organized into a data grid before being ready for analysis to correct the coordinates and amplitudes. The output of this step is a two-dimensional grid of pre-processed GPR profiles.

Step 4 Processing GPR data: In principle, there are two interrelated tasks in this step, (a) identify corrosion-induced defects. Specifically, the analyst may scroll each GPR profile and mark the deteriorated regions in different colors according to their severity as shown in Fig. 2. Areas marked in yellow show probable moderate corrosion and areas marked in red show high probability of severe corroded areas, while the unmarked regions refer to sound concrete, and (b) eliminate anomalies that are unrelated to rebar corrosion, e.g. existence of structural element, previous repairs, rebar spacing, etc. Generally, step 4 (processing GPR data) is based on the inspector’s experience and understanding of the inspected structure.

![Fig. 2. Marking Deterioration Regions on GPR Profiles](image)

Step 5 Map the deteriorated zones identified by GPR image-based 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 the structure is produced by connecting the same region types from separate scanned lines. The corrosiveness of concrete could be identified based on the degree of signal attenuation in these profiles. According to the signal attenuation, the concrete can be classified into three states: (i) sound concrete, (ii) concrete with moderate corrosion, and (iii) concrete with severe corrosion as identified in Table 1.

Table 1. Typical Definition of Various Conditions Using Image Analysis of GPR Profiles

<table>
<thead>
<tr>
<th>Probable Sound Concrete</th>
<th>Probable Moderate Corrosion</th>
<th>Probable Severe Corrosion</th>
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<tr>
<td>Rebar reflection is strong, uniform and clear with hyperbola shape.</td>
<td>Rebar reflection is relatively weak but hyperbola shape is still clearly visible.</td>
<td>Strong attenuation at top rebar level; hyperbola shape from rebar reflection is distorted or almost disappear.</td>
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</table>
4 Image-Based Versus Numerical Analyses

The various cases of signal attenuation together with their causes are highlighted in order to clarify the concept of visual image-based analysis method. Fig. demonstrates signal attenuation in the two marked locations. However, in the left marked location, GPR is not producing any signal reflection upward once more to be measured at the receiver, simply because there is a supporting beam in this location. On the other hand, in the right marked location, there is gradual signal attenuation, characterized by a bottom sagging which indicates that the attenuation is due to corrosion anomaly. The in-between signal is shown to be strong indicating a healthy concrete.

![GPR Profile of a Structural Beam, Compared to Corrosion](image)

Fig. 3. GPR Profile of a Structural Beam, Compared to Corrosion

Fig. combines different causes of signal attenuation. The first marked area of signal attenuation (left) is caused by existence of expansion steel joint. The second attenuation (middle) is caused by a cut in asphalt and repair in concrete causing the shown signal distortion. Deformation of the hyperbola is seen at the third marked area (right); indicating probable delamination and corrosion.

![Signal Attenuation Due to Different Anomalies and Defects](image)

Fig. 4. Signal Attenuation Due to Different Anomalies and Defects
Fig. shows aligned and staggered rebars to be the cause of GPR signal attenuation in this concrete structure. This case also reflects different causes for the attenuation of a GPR signal, other than defects in concrete.

An analyst can visually assess the above mentioned anomalies (presence of beam, expansion joint, cut in asphalt and repair in concrete, aligned and staggered rebars) and doesn’t mark them while he marks only the defects, this distinction cannot be made using numerical analysis.

Overall, the above mentioned cases explain different concepts of the image-based analysis method of GPR scanned profiles. All of which are directly applied and simply integrated in a software application to interpret image data, as shown in Fig. 2. The marked areas are then allocated on the bridge map to show the probable corrosion areas that comprise the map for the entire deck.

5 Methodology Implementation to a Case Study

The proposed image analysis methodology was used to assess the condition of a concrete bridge deck. The results of the image-based analysis and numerical analysis are both presented and compared for a case study in Montreal (Highway 40 Bridge). This bridge has severe rebar corrosion and concrete spalls that can be observed at several locations at the slab underside. The research team scanned the entire deck with GPR and mapped the probable corrosion activity. For each direction, 34 surveying lines were set up at 0.3m spacing. The deck was scanned by GSSI ground-coupled radar system (SIR-3000 and Antenna model 5100-1.5GHz). Collected data was then processed using both analysis methods, i.e., numerical analysis and image-based analysis of GPR profiles.
As for numerical analysis, Fig. presents various problems facing the analyst when processing GPR data for this case study. First, due to chaotic reflections caused by real defects or by structural/material configuration, rebar reflection cannot be picked at many locations, although for some areas this reflection is visible. Second, this structure is a tough test for GPR interpretation, because of the 15-17 cm of asphalt pavement on top of 30-35 cm of concrete slab. The slab bottom is not very recognizable in the GPR data collected from this structure.
To verify the robustness and accuracy of the image-based analysis, a deterioration map was prepared using the two methods, i.e. numerical analysis and image-based analysis as seen in Fig., and the results were compared. The accuracy of each condition map is then assessed based on signs of deterioration observed at the deck underside. Prior to conducting numerical analysis and producing a map, a depth-correction was applied (log-linear, with normalized dB on vertical axis and two-way travel time on horizontal axis). Fig. shows good correlation between the conditions provided by the image analysis of GPR profiles and the actual deterioration observed at slab bottom. Photo analysis for the bottom of the deck show deterioration signs and patterns that coincide with GPR map produced by image-based analysis. This is not the case for the attenuation map derived from numerical analysis, where there is no apparent similarity. The non-uniformity of the bridge deck structure, along with other factors discussed previously, may have affected the accuracy of numerical analysis results in this case. This proves the consistency and high accuracy of image-based analysis, which is also faster and less sensitive to the data quality compared to numerical analysis.

Fig. 8. Correlation between Image Analysis of GPR Profiles and Deterioration at Slab Bottom

6 Conclusion

In this paper, the corrosion mapping procedure based on GPR image analysis, is explained and validated. A step by step methodology is presented to identify and map corrosion anomalies in GPR profiles of concrete structure. The case study
demonstrated the superiority of GPR image analysis procedure over the commonly used numerical analysis. In this case study, the image-based analysis approach has generated a corrosion map that correlates much better with the available ground truth and the deterioration pattern observed on the underside, while conventional amplitude mapping failed to deliver meaningful results for this complicated structure. Image-based analysis uses the full information content in a GPR profile, most of which is ignored by the numerical analysis, eventually leading to errors and a noisy map. GPR image analysis offers clearer and more accurate results by eliminating the discrepancies of numerical amplitude analysis such as different anomalies unrelated to structural defects. This provides strong evidence to the fact that computer-assisted image-based analysis provides accurate corrosion mapping in concrete structures for comprehensive non-destructive condition assessment.

References