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A NEW APPLICATION OF THE GPR TECHNIQUE TO REINFORCED CONCRETE BRIDGE DECKS

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ABSTRACT

The half-cell potential test is the most widely used test to assess the likehood of rebar corrosion in reinforced concrete bridge decks. This test is however semi-destructive and necessitates the closure of the bridges for several hours. Because of these limitations, bridge engineers prefer to use the ground penetrating radar (GPR) technique. This non-destructive testing technique is still not really accepted by bridge engineers because its reliability is insufficient. This paper presents a novel methodology of GPR data processing that allows the detection of areas of high probability of rebar corrosion in concrete. This procedure gives results that are similar to those of the half-cell potential test. Its practical value and limitation are demonstrated using case histories.

INTRODUCTION

In North America, corrosion of steel rebar is the greatest factor in limiting the life expectancy of reinforced concrete bridge decks. This phenomenon is essentially caused by the excessive use of chloride de-icing salts during winter for the maintenance of the highways. The half-cell potential test is the most widely used test to assess the likehood of rebar corrosion. This test does not allow the detection of delamination in a direct manner. It provides an indication of the state of corrosion activity, and in some cases information on the possible presence of damage if this corrosion is in advanced stage. The inconvenience of this test is that is destructive and necessitates the closure of the bridges for several hours, which is problematic in urban areas such as Montréal or Toronto. Because of these limitations, bridge engineers prefer to use the ground penetrating radar (GPR) technique. This choice is justified by the fact that this electromagnetic technology makes it possible to collect the data in a fast way to avoid the indirect over-costs related to the temporary closing of bridges. Unfortunately, the GPR technique is not yet completely accepted by engineers because its reliability towards the detection of delamination is not satisfactory.

A research project was undertaken in 1999 by the research group on NDT and instrumentation (Université de Sherbrooke). The objective of this project was to define the manner the GPR technology can be better exploited by bridge engineers. During this project, GPR surveys were conducted on thirty concrete bridge decks. The results of these surveys were compared with the half-cell potential (HCP) data of these structures. The summary of this project is discussed in the following sections.

PRINCIPLE OF THE HALF-CELL POTENTIAL TEST AND THE GPR TECHNIQUE

Basically, the half-cell potential (HCP) test (ASTM, 1995; Berke and Hicks, 1990) assesses the condition of the steel embedded in concrete with regard to corrosion activity. In this method, the electrical potential (in mV) between a steel rebar and a reference electrode, usually a copper/copper sulphate cell, in contact with the concrete surface, is measured. This contact is done by water filling a hole drilled through the asphalt coating. A grid pattern is used to identify locations where the half-cell is to be placed to obtain potential measurements. In this study, this grid was fixed to 1 m $\times$ 1 m. The HCP values are plotted on schematic diagrams of the structures as an equipotential contour map. The ASTM Standard (ASTM C876-91, 1995) states that the probability of corrosion is less than 10% if the potential is greater than -200 mV, whereas potential values lower than -350 mV indicate a high probability (> 90%) that corrosion is active. Values between these limits indicate areas where the corrosion activity is uncertain.

The principle of the GPR technique (Alongi et al., 1992; Trottier and Barnes, 1998; Maser, 1991) is similar to that of the acoustic sonar. A high frequency electromagnetic wave is emitted via an antenna into the material under investigation. The reflected energy caused by changes in the electromagnetic properties within the material is detected by a receiver antenna and recorded for subsequent analysis. In bridge decks, these reflections are produced at the asphalt-concrete interface, at the top and lower rebar mesh and at the bottom of the deck (Figure 1). Modern GPR equipments collect radar waveforms at more than 100 signals per second. This high acquisition rate allows for data to be collected at driving speeds along the longitudinal dimension of the decks with the antennas fixed at the rear or in front of the vehicle. In our experiments, several parallel survey lines spaced out by 50 cm were made to cover the surface of the deck investigated. Longitudinal positioning of the data was done with the use of a distance transducer connected to the drive train of the data-collection vehicle.

EXPERIMENTAL PROGRAM AND RESULTS

To evaluate the reliability of a GPR survey, it is important to consider the two factors affecting this reliability, namely data quality and data processing. The data quality depends on the capacity of the GPR system to highlight discontinuities within the medium, and on the adequate adjustment of the system set-up parameters carried out by the operator (ex. sampling rate frequency). On the other hand, data processing involves using signal processing tools to extract the desired information from the collected data. The data processing approach must first be defined by the identification of the GPR signal parameter most sensitive to the information looked-for.

Field investigations were primarily performed on two asphalt-overlaid bridge decks in order to identify the GPR equipment that gives the best data quality and which is most suited to the problem considered herein. The performance of the four main GPR systems used for the evaluation of the condition of concrete bridge decks was studied. The GPR surveys were performed at low traffic speed (≈ 3 km/h), the same day and along the same survey lines. The quality of the data was evaluated according to the ability of the GPR systems used to detect the different interfaces within the decks. This study (Rhazi, 2000) showed that the GPR system manufactured by GSSI (SIR-20) with ground coupled antenna of 1.5 GHz gives the most interesting results. This system was used to collect the data on the other bridges investigated.

To identify the data processing approach that leads to the most reliable results, a comparison of the various existing procedures was carried out**.** These procedures as well as the results of their application to the GPR data collected in field are presented in Rhazi (2000). The synthesis of these results indicated that available GPR data processing approaches do not give conclusive results with regard to the detection of damage in reinforced concrete. A new data processing approach was then developed and validated. This approach relies on the ability of the GPR technique to detect the causes of corrosion initiation and growth (moisture and ions chloride). Specifically, the methodology consists in the measurement of the amplitude of the electromagnetic (radar) wave reflection at the concrete surface. If these amplitudes are normalized with regard to the amplitude of the transmitted waves by the antenna, then the variation of these reflections at the concrete surface can be computed. The scale of this variation (in dB) has been designed as the Radar Corrosion Index (RCI). It has been found that lower values of the RCI correspond to low corrosion probability whereas the higher RCI values correspond to high corrosion probability. In our experiments, the results of this data processing approach were compared to those obtained with the half cell potential test since both these techniques are sensitive to the electrical conductivity of concrete.

Figure 2 give the contour plots of the half-cell potential (in mV) and the RCI (in dB) data in the case of three concrete bridge decks: A, B and C. The vertical axis of these plots (X) represents the length of the deck (in m), and the horizontal axis (y) the width of the deck (in m). On the corrosion potential maps, black areas correspond to HCP values below -350 mV which, according to the ASTM criterion (ASTM C876-91, 1995), indicate high probability of rebar corrosion. On the RCI maps, black areas correspond to highly reflecting and so potentially corroded areas. The choice of an RCI threshold is depending on the bridge investigated. For each bridge, an optimal RCI threshold is determined by varying step by step the RCI value in order to obtain the best graphical correlation with the HCP maps. Table 1 shows the optimal RCI threshold corresponding to each bridge deck. Thereafter, the thresholds determined in a graphical way were found to approximately correspond to the most frequent values of the RCI frequency histograms. Thus, it would be possible to define an RCI threshold in a less subjective way.

The data processing approach presented above has some disadvantages. In particular, when the asphalt layer which covers the deck is thin (< 7 cm), it can be observed interference between the last peak of the direct wave propagating in asphalt and the first peak of the asphalt-concrete reflection (Figure 1). Considering the GPR system used in this study, these two peaks are generally positive, generating constructive interference. Thus, the amplitude of the signal reflected by the asphalt-concrete interface may be increased by this phenomenon and areas with thin asphalt layer may appear virtually more reflecting. Since RCI is calculated with respect to this amplitude, these areas are consequently affected by a high RCI value, while, actually, they are not necessary subject to reinforcement corrosion. So, before the calculation of RCI, it is important on each GPR profile to search for interference between these two signals and eventually to correct it if possible.

To overcome these problems, a second data processing approach was tested. This approach considers the attenuation of the radar wave during its propagation in concrete. Figure 1 shows the correlation between this second GPR data processing approach and the first one presented above. It can be observed that when the reflection amplitude at the concrete surface increases at the distances of 137.5 m, 140-146 m, 149 m and 156 m, the attenuation of radar waves in concrete is high and the reflection of the wave at the bottom side of the deck is not visible in the GPR data.

Figure 3 shows an example of the correlation between radar wave attenuation and HCP data. This correlation was observed on most of the bridge decks investigated. It was found that the attenuation is low when the HPC value is high (>-350 mV), and the attenuation is high when the HPC value is low (<-350 mV) (Rhazi and Dous, 2005).

The explanation of the correlation between the HCP data and radar wave attenuation can be based on the electrical resistivity (ρ) of the concrete.

Figure 4 gives the variation of the HCP data with electrical resistivity of concrete. This correlation was obtained upon more than 400 measurements on structures in service. Electrical resistivity measurements were done at the same locations as the HCP measurements with a

Wenner probe. The dispersion of the data is notable because electrical resistivity of concrete vary in a large manner in concrete (from Ω.m to MΩ.m). However, globally, electrical resistivity values increase when the HCP values increase, which is in agreement with previously published results on this subject. The approximation of the correlation by an exponential curve is also presented in figure 4. It can be shown that the HPC value of -350 mV correspond approximately to the resistivity value of 100 Ω.m. Hence, areas of the reinforced concrete bridge decks with high corrosion probability of rebar have electrical resistivity lower that 100 Ω.m.
Figure 5 gives the correlation between the attenuation of radar wave in concrete and the electrical resistivity of concrete. This correlation is obtained from the equation of electromagnetic wave propagation in concrete (Alongi et al., 1992) with a relative permittivity (ε'_r) of 9 and a wave frequency of 1 GHz. As shown in this figure, the attenuation is negligible for high electrical resistivity and its effect on wave propagation becomes at a resistivity value lower than 100 Ω.m.

CONCLUSION

In the light of the results presented in this paper, it appears possible to characterise the corrosion activity in reinforced concrete bridge decks by means of the radar waves attenuation in concrete.

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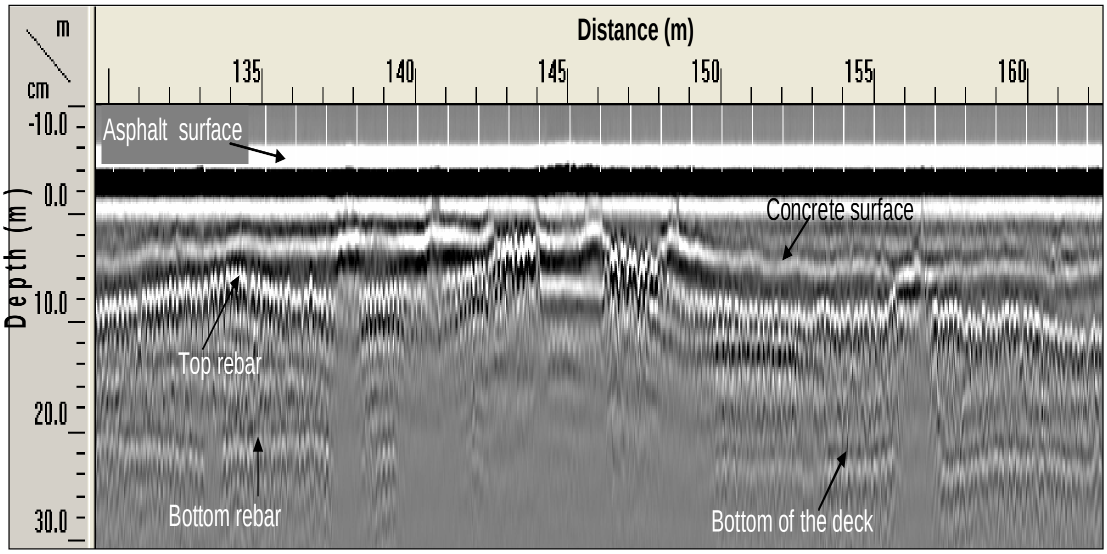
Figure 1



m
cm
Distance (m)
135
140
145
150
155
160
Depth (m)
-10.0
0.0
10.0
20.0
30.0
Asphalt surface
Concrete surface
Top rebar
Bottom rebar
Bottom of the deck

Figure 2

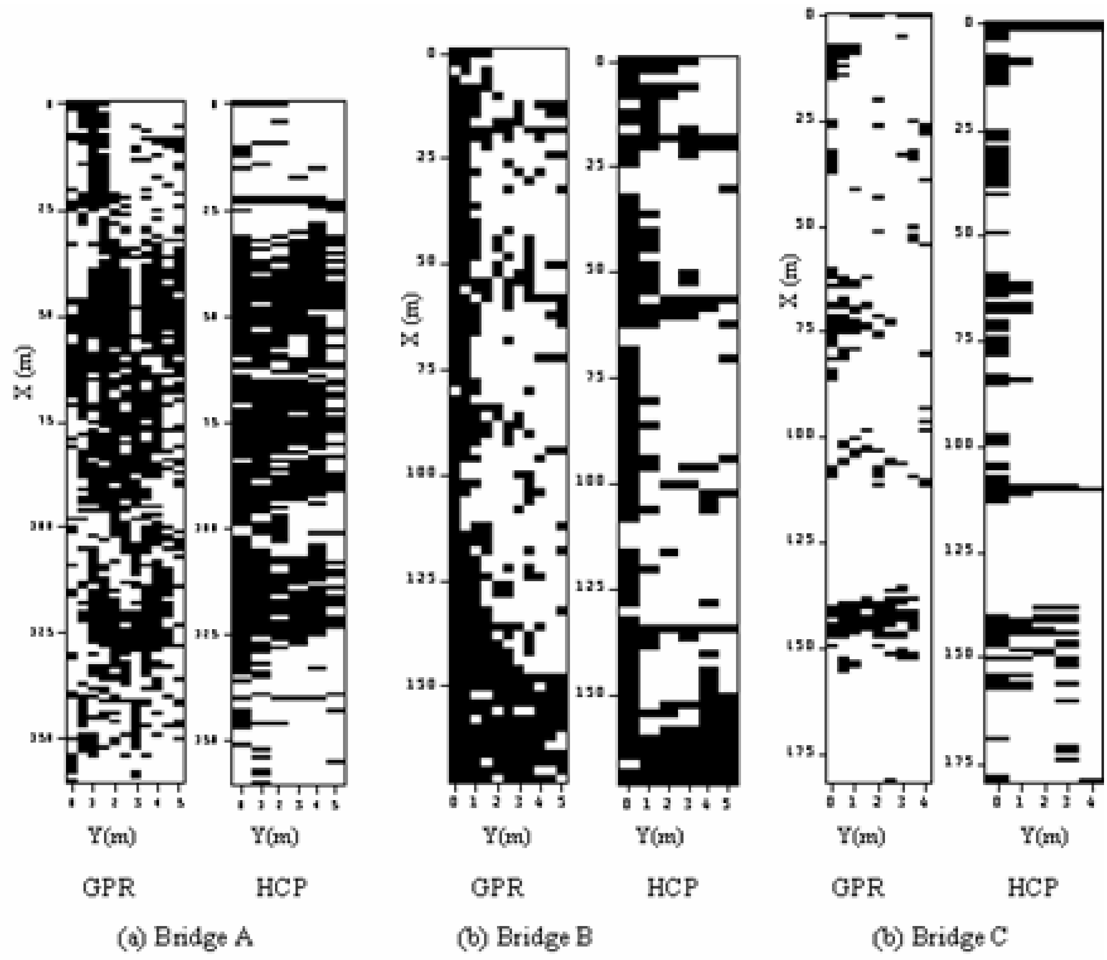
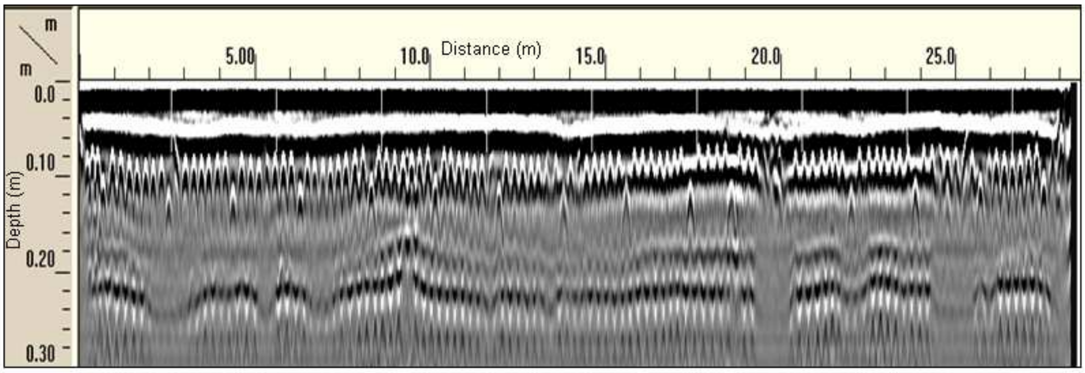
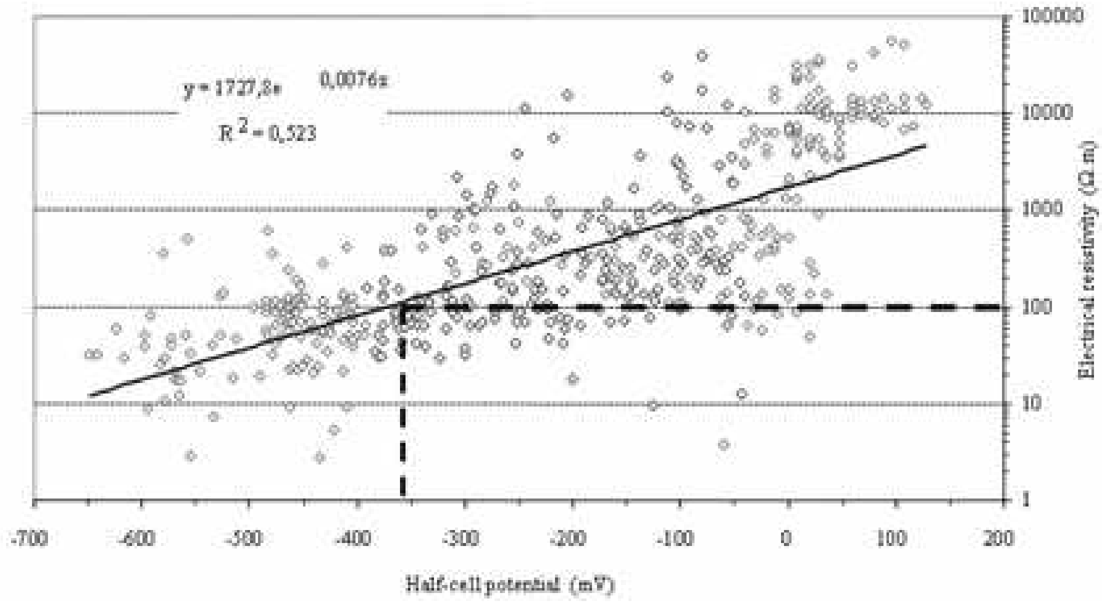


Figure 3



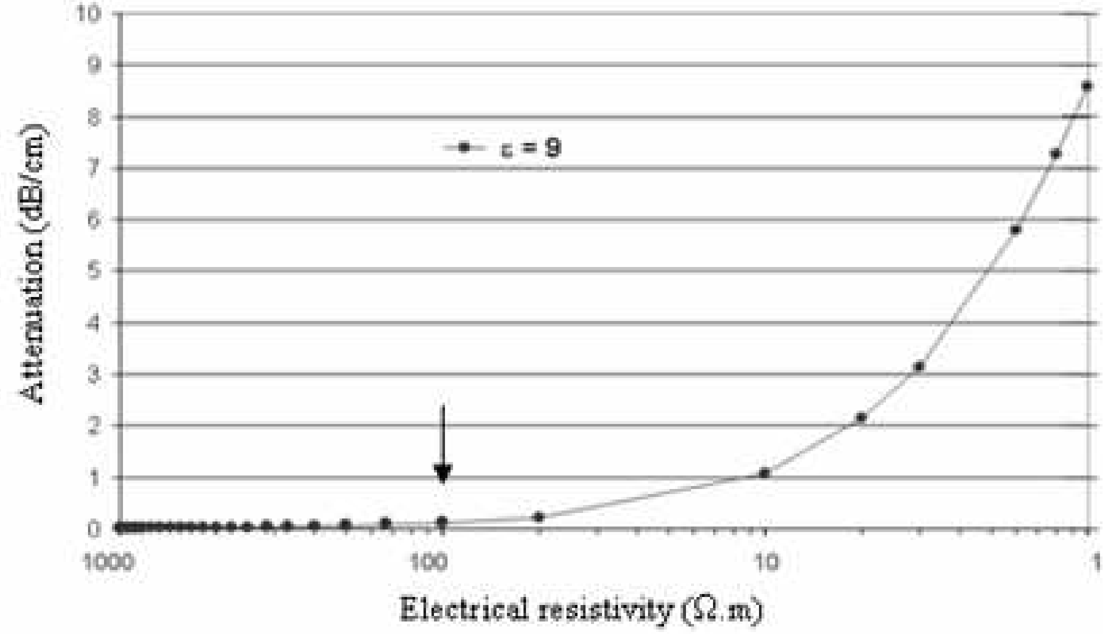
HCP:	259	106	295	206	271	143	75	128	85	236	175	90	102	421	53	90	201	525	28	73
D (m) :	0	1,5	3	4,5	6	7,5	9	10,5	12	13,5	15	16,5	18	19,5	21	22,5	24	25,5	27	28,5

Figure 4



y = 1727,8e 0,0076x
R 2 = 0,523
100000
10000
1000
100
10
1
Electrical resistivity (Ω.m)
-700
-600
-500
-400
-300
-200
-100
0
100
200
Half-cell potential (mV)

Figure 5



10
9
8
7
6
5
4
3
2
1
0
Attenuation (dB/cm)
ε = 9
1000
100
10
1
Electrical resistivity (Ω.m)

Table 1

Bridge deck	Optimal RCI threshold (Comparison with HCP maps)	Most frequent value of the RCI frequency histogram
A	-7 dB	-7,5 dB
B	-17 dB	-18 dB
C	-11 dB	-13 dB

FIGURE AND TABLE CAPTIONS

Figure 1: Example of GPR data collected on a reinforced concrete bridge deck
Figure 2: Comparison of the GPR and HCP results
Figure 3: Correlation between radar wave attenuation and half-cell potential
Figure 4: Experimental correlation between the HCP and electrical resistivity of concrete
Figure 5: Radar wave attenuation vs. electrical resistivity of concrete

Table 1: RCI Value above which the probability of corrosion is high