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Method for attenuation assessment of GPR data from concrete bridge decks

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ABSTRACT

Ground penetrating radar (GPR) is a well-accepted technology for condition assessment of concrete bridge decks. Such assessment has been mainly based on the measurement of attenuation of a signal reflected from the top rebar mat. Recently, a new approach for GPR data interpretation has been proposed, which is based on the correlation analysis of time-series GPR data. Motivated by that same research, the current paper presents an alternative method for performing the GPR attenuation analysis. In this method, instead of requiring time-series or baseline data, semi-simulated waveforms are developed and employed in a correlation analysis. With only one reflection retained from direct coupling, these waveforms mimic A-scans collected on a completely deteriorated bridge deck. The obtained results are then plotted in a form of contour maps of correlation coefficients, in which a higher value coefficient indicates more deteriorated concrete. The method was validated through its implementation on three bare concrete bridge decks. The condition maps from the proposed GPR correlation analysis correlate well to those obtained using the conventional GPR amplitude approach, and condition maps from several other nondestructive evaluation (NDE) techniques. However, in comparison to the conventional amplitude analysis, the proposed method provides a better description of the overall deterioration of bridge decks.

1. Introduction

Ground penetrating radar (GPR) is a well-accepted nondestructive evaluation (NDE) technology for identifying and quantifying deterioration of concrete bridge decks [1,2]. The technology has been extensively researched, and adopted through an ASTM standard [3]. Whereas many advanced procedures for interpreting GPR data have been proposed [4–10], the ASTM standard still recommends the use of a rather simple approach. Specifically, the approach simply compares the reflection amplitudes between rebars or slab bottom locations from the same bridge deck. The condition at a specific rebar or location is then evaluated based on the amplitude difference with respect to the ones that have the strongest reflection. The higher the difference, the more severe deterioration will be anticipated. If we assume that these referenced rebars or slab bottom locations also deteriorate over time, which will most likely be the case, the overall deterioration of a bridge deck will certainly be overlooked.

2. Research objectives

Motivated by the aforementioned problem, the main goal of this study was to develop an analysis method that can better assess the GPR signal attenuation in concrete bridge decks. To achieve that goal, two research objectives were identified as follows:

(i) To critically review approaches used in GPR condition assessment of concrete bridge decks, and
(ii) To compare results from the proposed and other approaches.

3. Methods for evaluating GPR data from concrete decks

Numerous studies have been conducted to understand and find the best approach for analyzing GPR data collected through surveys of concrete bridge decks. As a result, several GPR data analysis methods have been proposed. These methods can be grouped into two main categories: *visual interpretation (qualitative)* and *numerical analysis (quantitative)* methods [6]. Since each method category has its own advantages and limitations, hybrid approaches have recently been proposed and introduced in the literature [8,10].

As an early effort with visual interpretation, Chung et al. [4] proposed using features of the shape of A-scans to analyze GPR data from a survey on an asphalt-overlaid reinforced concrete bridge deck

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collected with an air-coupled (horn) antenna. It was based on the analysis of the expected shapes of waveforms if they are collected at sound, debonded or delaminated concrete locations. This method is, however, difficult to employ. Specifically, the shape of an A-scan can vary greatly, even for sound concrete areas. It is subjected to the GPR equipment used, the shape of transmitted pulse and the variation in thickness of various layers. In addition, while the main defects of concern in that research were debonding and delamination, it is now very well understood that GPR is not a good technology for detecting thin delamination [11]. Instead, it has been proven to be an effective technology for identifying concrete's corrosive environment [6,8,9].

As the separate analysis of individual GPR A-scans provides a rather limited insight about the structural condition, Tarussov et al. [6] developed a new procedure to visually analyze B-scans (GPR profiles). In this method, the analyst will scroll through individual GPR profile and mark suspected damaged areas based on his/her experience. The results will then be combined for all the profiles of a bridge deck to generate a GPR condition map. The speed of the data analysis, and the ability to eliminate amplitude anomalies caused by thickness variation, rather than corrosion-induced defects, were cited as the benefits of this method.

Still, the most commonly-used procedure to analyze GPR data from concrete bridge deck surveys is the one guided by the ASTM standard [3]. The standard recommends that the condition map be developed based on the GPR signal attenuation measured at either the slab bottom or the top reinforcing mat level. With respect to the latter method, although a −6 to −8 dB signal attenuation was defined in the standard as the deterioration threshold, these threshold values are still a research topic. Most recently, Martino et al. [7] tried to develop a threshold model based on the distribution of depth-corrected amplitude, while Dinh et al. [8] developed a model to determine flexible amplitude thresholds based on the K-means clustering technique. The latter model is a hybrid approach, since the visual interpretation is employed in one step of the data analysis process.

In another effort to simulate the visual interpretation that takes into consideration the information of entire GPR signals, Dinh et al. [10] developed a method based on correlation between A-scans. However, since the method can only be implemented with a time-series or baseline data (data collected when a bridge deck is new), it is limited to bridges for which baseline data exist. That problem is resolved in the current research.

4. Research methodology

As described above, the visual interpretation methods consider the geometric features or characteristics of either entire A- or B-scans. However, those are subjective to each data interpreter. On the other hand, while the analysis based on the ASTM standard is objective, it only analyzes a small piece of information extracted from the GPR data. In the ASTM standard, the term "***attenuation***" is defined relatively, as the amplitude difference between reflections from reinforcing bars. As can be imagined, in an ideal case where an entire bridge deck is corroded and, thus, all reflection amplitudes are weak, but not much different, the bridge would be misinterpreted as being in a good condition. Such an example has been presented and discussed in the literature in which the ASTM-based amplitude analysis suggested the improvement of the condition of a bridge deck over time [10]. In the following paragraphs, a methodology to evaluate attenuation of a single A-scan is, therefore, described and discussed.

The methodology was motivated by an observation of a B-scan from a ground-coupled GPR antenna shown in Fig. 1. As can be seen, while the reflections at the top/bottom rebar mat and slab bottom levels are very sensitive to concrete deterioration, the first reflection, i.e., direct coupling, is much more stable. In addition, for a more deteriorated concrete, the reflection amplitude at the top/bottom rebar and slab bottom levels reduces and tends to disappear in the GPR image (B-scan). For the, theoretically, worst condition, the signal will be completely attenuated and there will be no reflections from these layers. The A-scan will have only one reflection peak, the so-called "direct-coupling". It is an effect that occurs when the antenna is moved toward a contact with the ground. When this happens, the "air wave", i.e., the direct wave between transmitting and receiving antennas, is coupled with the surface reflection to create a mixed waveform that is called "direct coupling". A signal (A-scan) close to this theoretically worst case scenario is provided in Fig. 2b, which is in contrast to the signal with a strong reflection collected above sound concrete depicted in Fig. 2a. In the figure, the B-scan is also included for clarity.

The above observations suggest a method to measure attenuation for the ground coupled GPR with respect to a single radar waveform. As an example, let us assume that an A-scan has been collected at a rebar location, as shown in the solid line in Fig. 3, and that it needs to be evaluated for the severity of deterioration. The proposed procedure has the following flow. First, a semi-simulated A-scan is created to mimic the one collected at a location of a completely deteriorated concrete. This A-

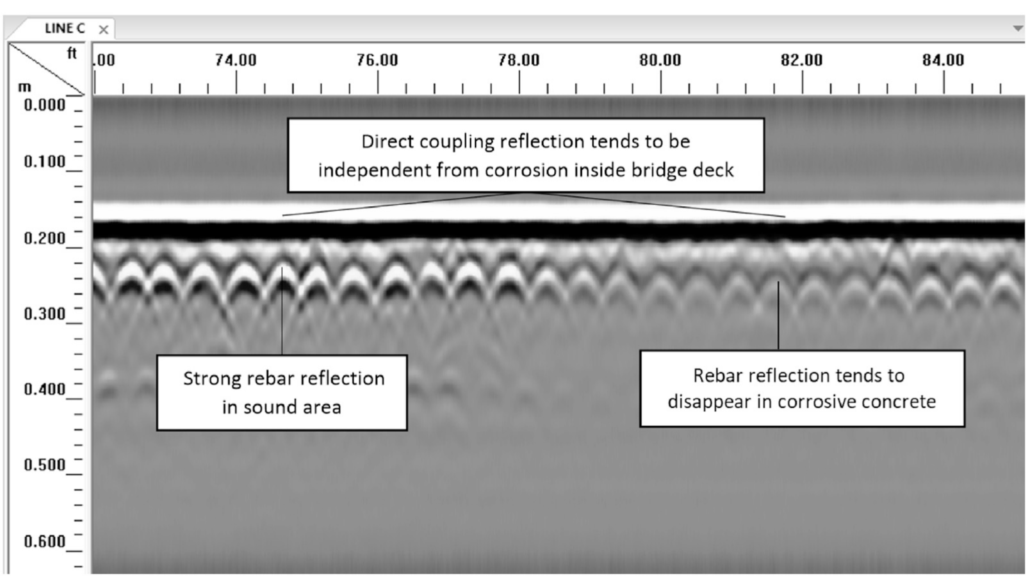

Fig. 1. Model motivation.

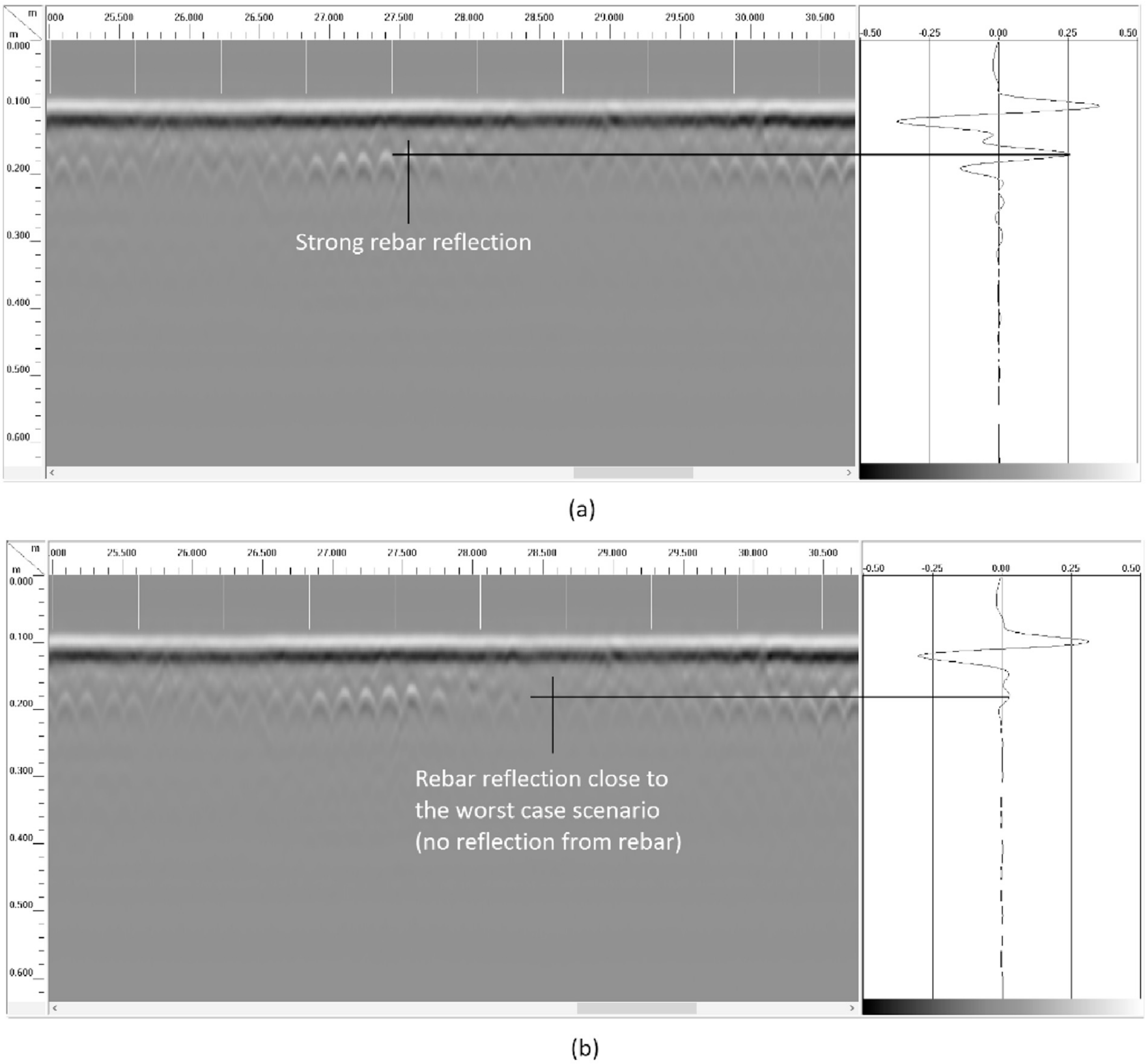

Fig. 2. GPR signals from (a) sound concrete and (b) highly corrosive concrete.

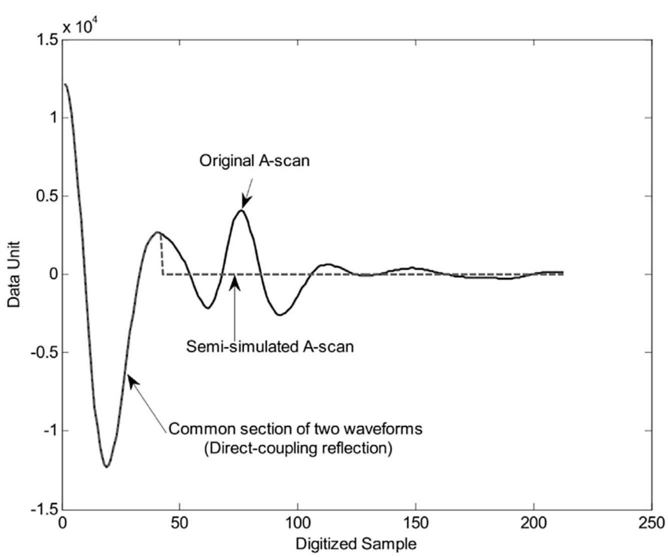

Fig. 3. Comparison between original and semi-simulated waveform.

scan, depicted in the dashed line in Fig. 3, has the same direct-coupling reflection as the original waveform. However, it does not contain reflections from any of the objects or interfaces. Then, the attenuation can be assessed by comparing the similarity between the two waveforms. Specifically, the more similar the two waveforms are, the more attenuated the original A-scan, and more deteriorated concrete will be.

To assess the similarity of signals, it is recommended that the same correlation coefficient ρ_{xy} proposed by Dinh et al. [10] be utilized. As defined by Equation (1), ρ_{xy} is simply the normalized covariance between two digitized signals/variables x_t and y_t.where:

$$\rho_{xy} = \frac{\gamma_{xy}}{\sigma_x \sigma_y} \tag{1}$$

$\gamma_{xy} = E[(x_t - \mu_x)(y_t - \mu_y)]$ is the covariance between x_t and $y_t$$\mu_x$ and μ_y are the means of x_t and y_t, respectively

σ_x and σ_y are the standard deviations of x_t and y_t, respectively

The closer the coefficient is to unity, the more attenuated the original waveform will be. In addition, it is noted that, in order to be consistent with future calculations of the coefficient, and specification of the coefficient threshold, this study suggests that only a 5-ns section of the signal be used in this approach. Since the propagation velocity of an EM wave in concrete is greater than 10 cm/ns [12], the 5-ns section is equivalent to about 0.25 m thick concrete deck. Therefore, it is enough to cover the thickness of most bridge decks. The rationale of using the correlation coefficient for evaluating attenuation of GPR signals is also illustrated in Fig. 4, where it is compared to the conventional amplitude analysis technique. As can be seen, the correlation coefficient has the same capability in detecting attenuated signals as the amplitude method. The lower the reflection amplitude at a rebar location is, the higher the correlation coefficient will be obtained for the A-scan at the same location.

To map the attenuation levels, the conventional contour mapping is employed in this study. A program written in MATLAB was developed to implement the entire process, as depicted in Fig. 5. First, the program reads each GPR profile and processes it to pick rebar locations. This is done by using a migration technique that focuses energy on true rebar locations. The picking is then performed by searching for pixels of high intensity, along with additional picking criteria, such as an anticipated depth of rebars or migrated shapes of reflections from reinforcing bars. The accuracy in rebar detection of the developed rebar picking procedure is higher than 95 percent. While the detailed description and explanation of the program will be the topic of a separate paper, an example of a profile with picked rebars is provided in Fig. 6.

Once the rebars are identified, the program extracts all A-scans at rebar locations. Each of these A-scans is then used to create a corresponding reference waveform (semi-simulated A-scan) for performing correlation analysis. Specifically, for each pair of signals, a correlation coefficient is computed and all correlation coefficients and their corresponding locations are then exported to a spreadsheet. The attenuation map is finally developed in the form of a contour map of correlation coefficients.

5. Case study implementation

The proposed methodology was implemented in the assessment of three bare concrete bridge decks. The same ground-coupled GPR system with a 1.5-GHz center frequency antenna was utilized in the evaluation of the three bridges. In addition to GPR, the three decks were surveyed using other NDE techniques. The condition maps from these technologies were used to assess and validate the proposed method. For each deck, data for all the technologies were collected on the same survey grid in which a 0.6096-m x 0.6096-m [2-ft x 2-ft] grid was set up and marked by chalk. The first line of the grid was offset 0.3048-m [1-ft] from the parapet.

5.1. Bridge in Haymarket, Virginia

Located on State Route 15 over Interstate 66 in Haymarket, Virginia, the bridge consists of a bare reinforced concrete deck on top of two-span continuous steel girders. The bridge was constructed in 1979. It is 86.5 m long and 11.5 m wide. The concrete bridge deck is 22 cm thick. The top mat of reinforcing bars is epoxy-coated, whereas the bottom mat consists of uncoated reinforcing bars. Four NDE technologies were deployed to scan the bridge in October 2014, including GPR, half-cell potential (HCP), electrical resistivity (ER), and impact echo (IE). It is important to note that although the top rebar mat of the deck was epoxy-coated, whether due to deterioration processes in the past 35 years or epoxy coating damage at the time of construction, the HCP measurements revealed values commonly observed on deteriorated decks with uncoated rebars. That was confirmed by checking the electrical connectivity of the top reinforcing mat at two distant locations before the HCP test.

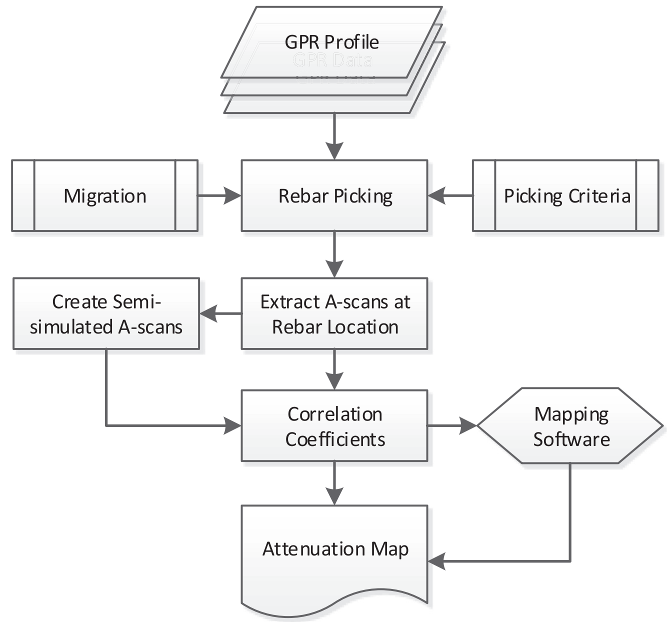

Fig. 5. Procedure for developing attenuation map for a bridge deck.

The attenuation map created using the proposed model is first compared to the one developed using a conventional depth correction technique [5]. As can be seen in Fig. 7, the areas of high attenuation in the two maps correlate very well. The two maps are then further compared to the results from other NDE technologies depicted in Fig. 8. Visually from the comparisons, it can be drawn that the GPR maps correlate the best with both the ER and HCP results. Numerically, the areas with the ER measurement lower than 40 kΩ cm in Fig. 8 appear to be at the same location as the areas with the HCP values lower than −350 mV. The areas with poor and serious conditions in the IE map appear to be slightly smaller than the deteriorated regions in both the ER and HCP maps. This is reasonable as it takes time for the delamination to develop after the corrosion is initiated in bridge decks. In addition, the best correlation between the GPR, HCP and ER can be explained due to

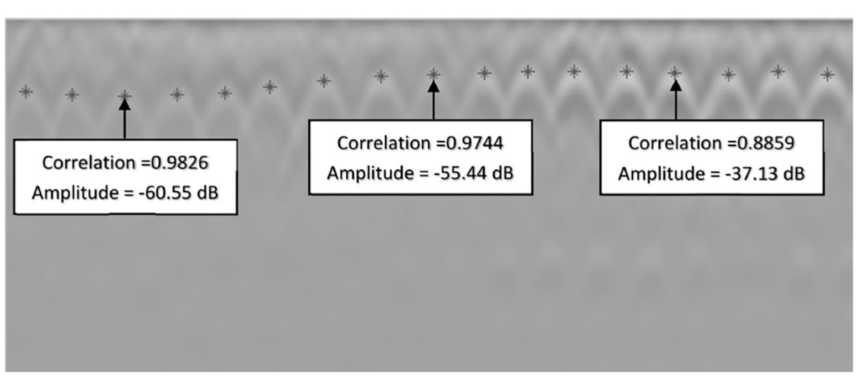

Fig. 4. Correlation coefficient versus amplitude in assessing attenuation of GPR data from bridge decks.

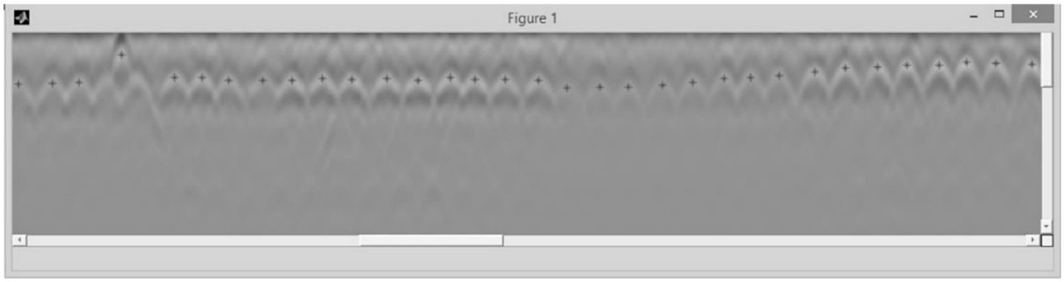

Fig. 6. Example performance of rebar picking algorithm.

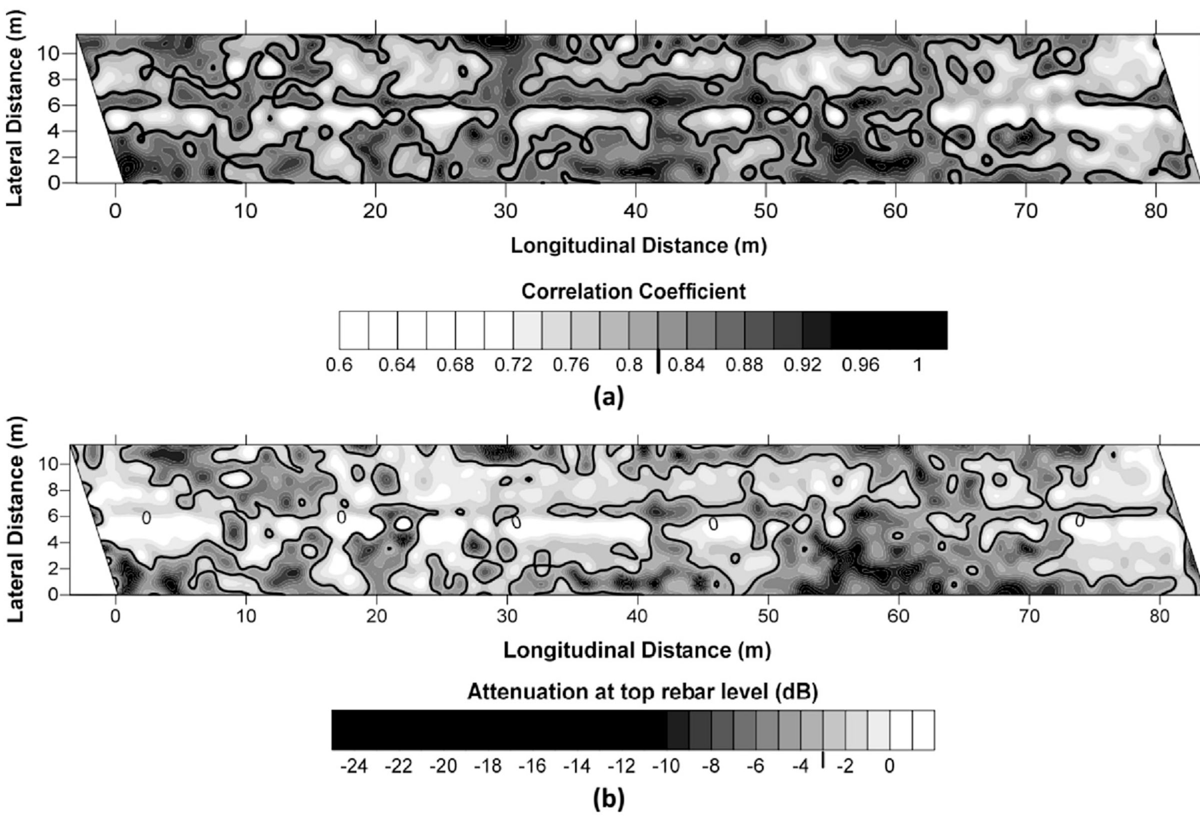

Fig. 7. GPR attenuation maps for the Haymarket Bridge deck with (a) Proposed method and (b) GPR amplitude analysis.

the fact that the results from three technologies are influenced by corrosive environment and corrosion processes in bridge decks. Therefore, based on the agreement with deteriorated areas in the ER and HCP maps, a threshold value is established for both GPR analysis techniques. As can be seen in Fig. 7, whereas the correlation threshold for the proposed method is 0.82, the attenuation threshold for the conventional technique is −3 dB.

5.2. Bridge in Pohatcong, New Jersey

The Pohatcong Bridge in Warren County, New Jersey, was built in 1978. It consists of a bare concrete deck resting on five single -span steel girders. The bridge is 36 m long and 11 m wide, and the deck is 25 cm thick. The deck was scanned in August of 2014 using three NDE technologies, namely: GPR, ER, and IE, and condition maps for all were generated.

As in the first case study, the attenuation maps were developed using both analysis techniques, i.e., the proposed and conventional depth correction methods. As depicted in Fig. 9, it is easy to recognize that the areas of higher attenuation from the two methods appear to be at the same locations. However, using the same thresholds established in the first case study, i.e., 0.82 and −3 dB, the absolute condition of the bridge deck obtained from the two interpretation techniques is significantly different. The proposed method suggests a much more severe condition for the bridge deck than the conventional amplitude analysis technique. Specifically, whereas the proposed method indicates that almost the entire deck area is deteriorated, the conventional technique suggests deterioration for less than half of the bridge deck area. As can be observed in Fig. 10, using the same thresholds from the first bridge deck study, the deteriorated area suggested by the ER technique is even slightly larger than the area defined by the proposed method. In addition, the delaminated area from the IE map (poor and serious) is significantly greater than a half of the bridge deck area. All these results indicate that the attenuation threshold of −3 dB established from the Haymarket Bridge deck is not appropriate for the Pohatcong Bridge deck. Instead, a greater threshold value (less negative value) should be employed to take into account the overall deterioration (attenuation) of the entire bridge deck. However, to define the amplitude threshold would require deployment and use of results from other NDE techniques.

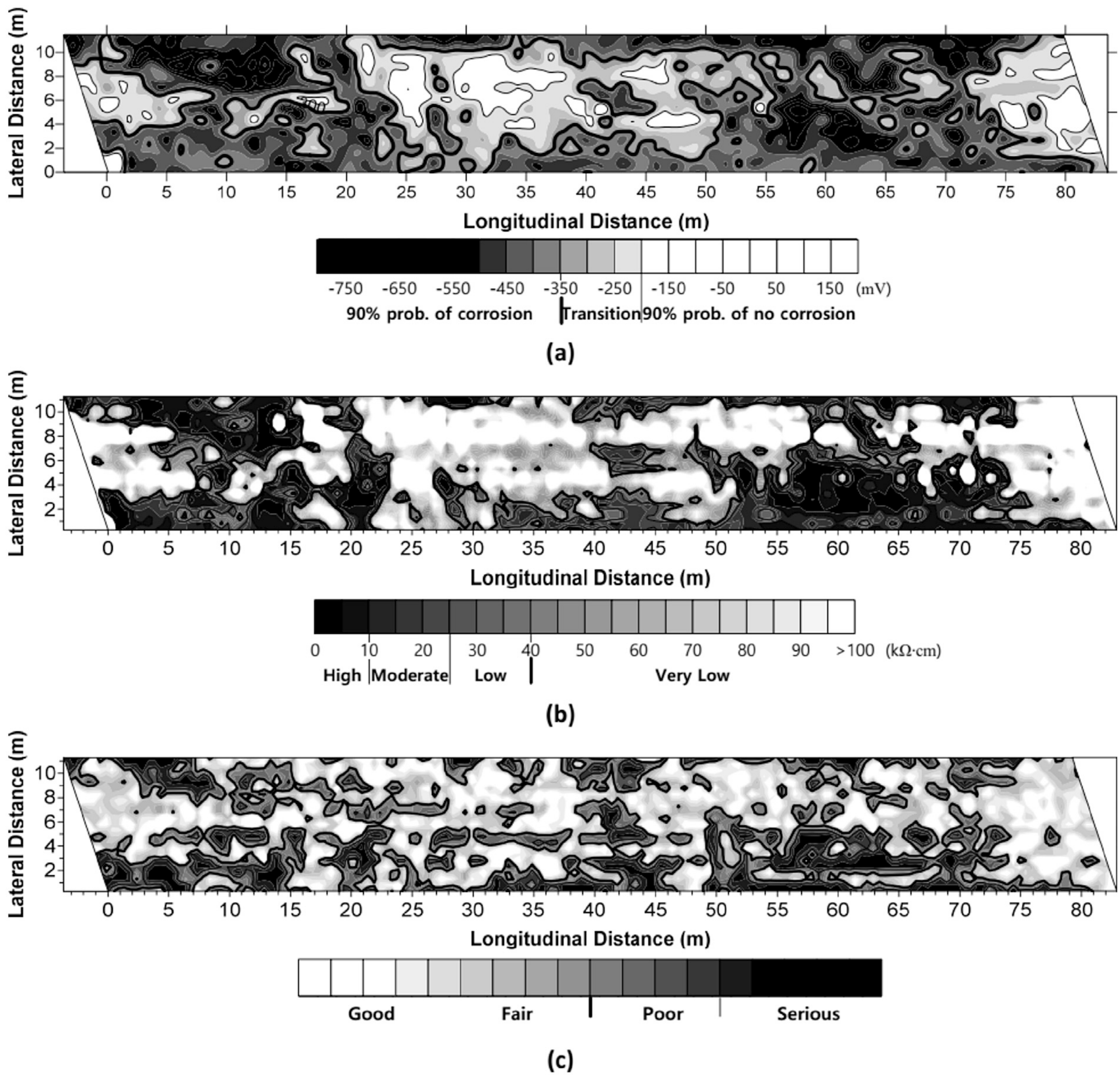

Fig. 8. Condition maps for the Haymarket Bridge deck for (a) HCP, (b) ER, (c) and IE.

5.3. Bridge in Elkton, Maryland

The bridge in Elkton, Maryland was built in 1973. It is located on State Route 273 and crosses over the Little Elk Creek. The bridge is 27 m long and 14 m wide. Its structure consists of a bare concrete deck, seven steel girders, two abutments and a pier. The bridge is skewed with an angle of 14°53'. The deck, which is 20 cm thick, was tested in July 2013 using GPR, ER, and HCP. The results are presented in Fig. 11 as an additional proof of concept of the proposed methodology.

In Fig. 11, the same thresholds as the ones used in the first two case studies are utilized. Specifically, for GPR, the correlation coefficient threshold is 0.82 whereas the amplitude threshold is −3 dB. It is noted herein that these two thresholds were established from the first case study by matching the deteriorated areas delineated by each GPR analysis technique with those identified from other NDE technologies' results.

With respect to the condition maps in Fig. 11, the same observations and explanations can be made as in the second case study. First, the GPR condition map obtained using the proposed method (Fig. 11a) describes more severe condition than the one developed using the conventional technique (Fig. 11b). Second, the severity suggested by the proposed method with the corresponding correlation coefficient threshold (0.82) is compatible with the deck condition described by ER (Fig. 11c) and HCP (Fig. 11d) results. Third, all the maps in Fig. 11 appear to be very well correlated. Some discrepancies between GPR condition maps and the maps obtained from ER and HCP may be contributed to the fact that the GPR assesses bridge decks with a higher resolution. Whereas ER and HCP measurements were performed on a 0.6096-m x 0.6096-m [2-ft x 2-ft] grid, the resolution for GPR assessment was 0.6096-m x *"rebar spacing"*. This rebar spacing may vary from bridge to bridge and even in the same deck, however, it is usually much shorter than 0.6096 m.

6. Discussion

The use of the semi-simulated A-scan in the proposed approach is the main contribution of this research. The idea of retaining the direct-coupling reflection and ignoring the rest in the semi-simulated A-scan is based on the concept of "template matching" or "pattern recognition" that is commonly used in computer vision. In the current research, since it is known in advance how the A-scan collected on a fully-deteriorated concrete deck will look like, i.e., the semi-simulated A-scan, one just needs to use that as a template for the study of attenuation. Thus, including the direct-coupling reflection in the semi-simulated waveform

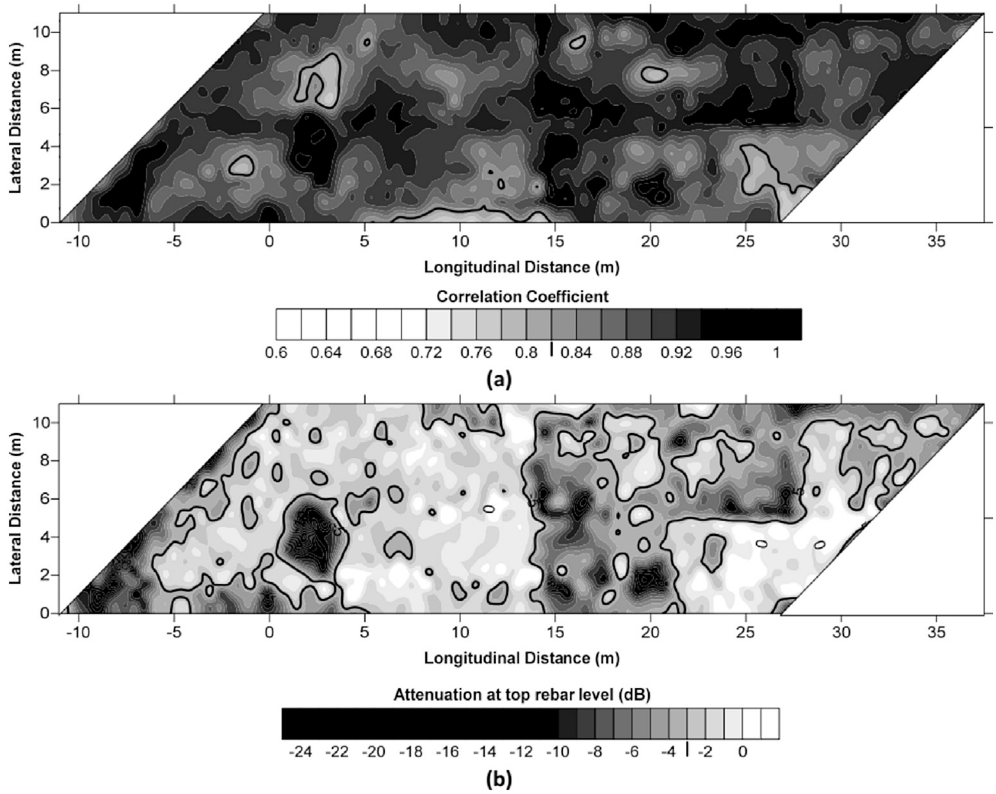

Fig. 9. GPR attenuation maps for the Pohatcong Bridge deck with (a) Proposed method and (b) GPR amplitude analysis.

is required. Otherwise, the waveform (A-scan) will simply be a zero signal that is not useful for extracting attenuation information from the original A-scan."

As presented, the three case studies clearly demonstrate the capability and the advantages of the proposed approach. The underestimation of deteriorated areas for the Pohatcong Bridge and the Elk Creek Bridge

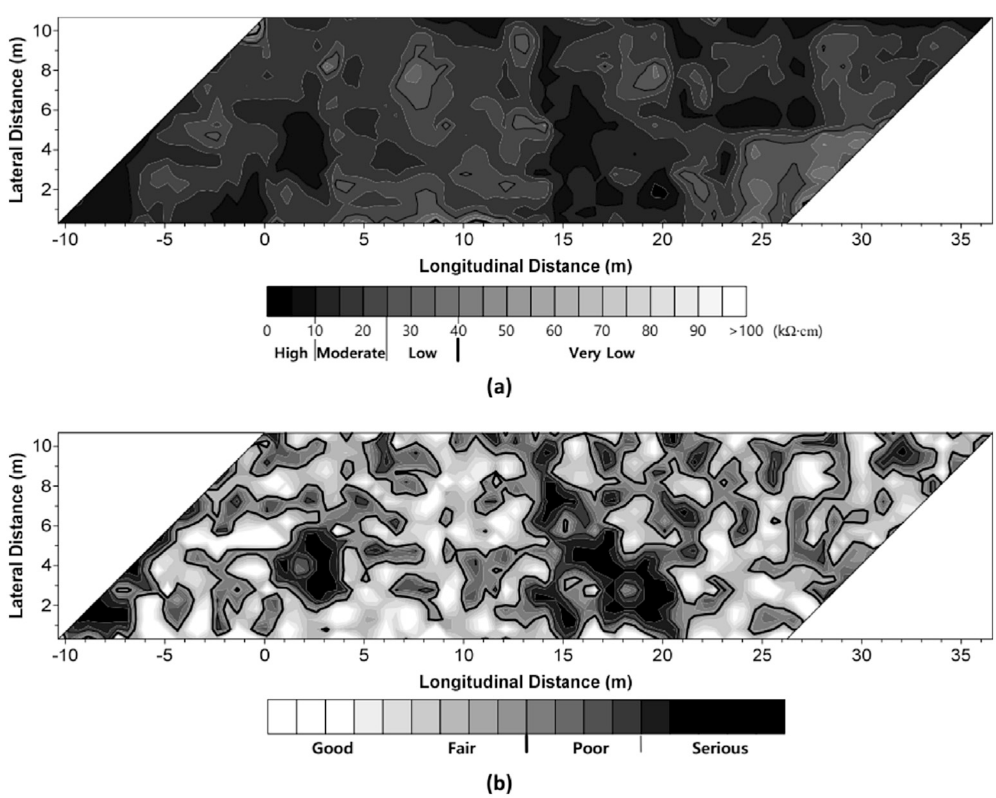

Fig. 10. Condition maps for the Pohatcong Bridge deck for (a) ER, and (b) IE.

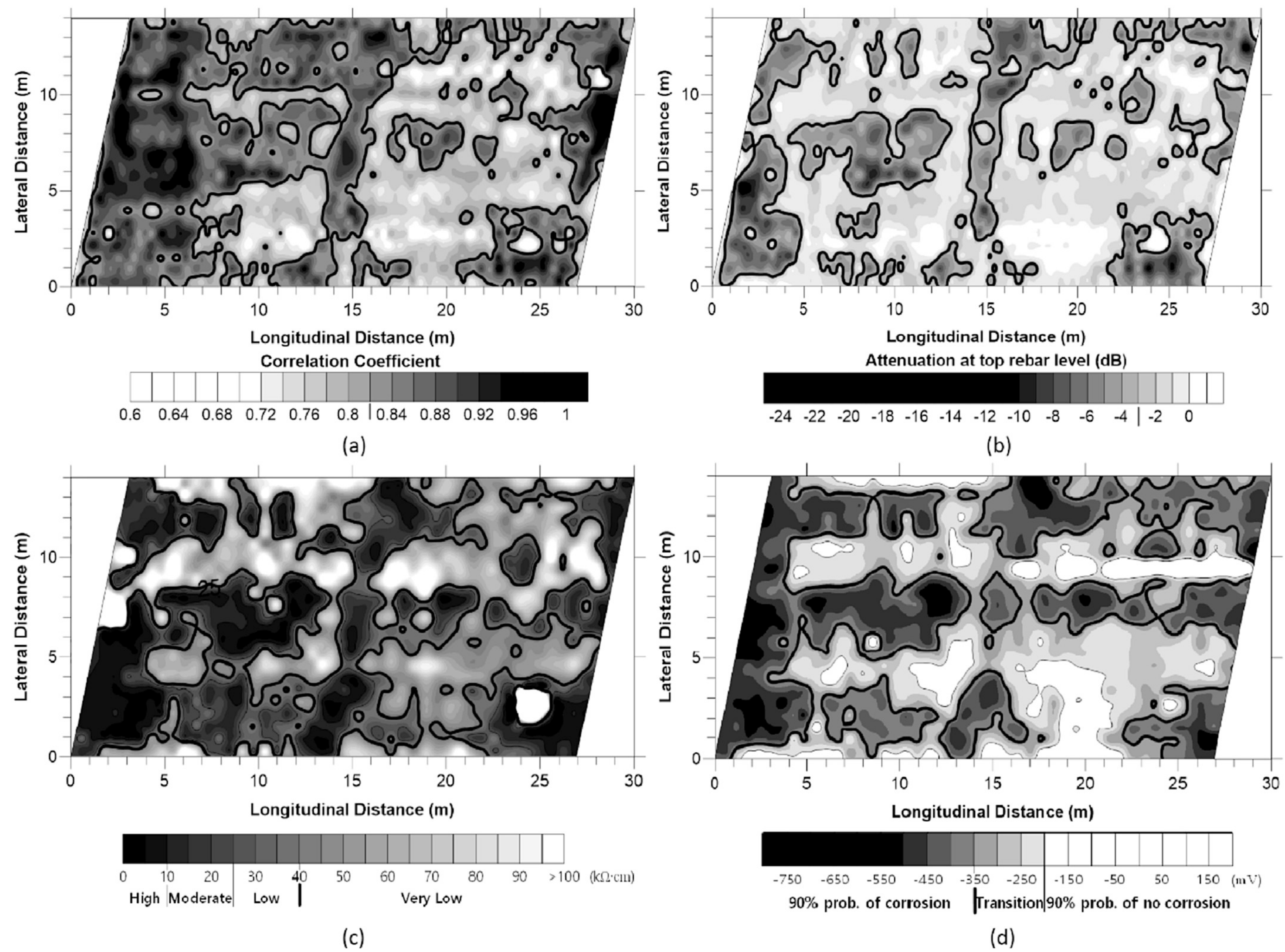

Fig. 11. Condition maps for the Elk Creek Bridge deck with (a) Proposed method, (b) GPR amplitude analysis, (c) ER and (d) HCP.

stemming from the use of amplitude analysis method is caused by the reduction of amplitude contrast due to the deterioration of the entire bridge deck. On the other hand, using the same correlation threshold, the proposed methodology provided a consistent estimation of deteriorated areas for the three bridge decks. As has been seen, these areas correlated very well with the deteriorated areas delineated by other NDE techniques. Obviously, the underestimation problem of the amplitude analysis method can be overcome, if other inspection techniques are used to assess the overall deterioration of bridge decks. However, if that is the case, GPR will not be considered as a stand-alone assessment technique.

By taking into consideration the reflection from all EM wave reflectors in bridge decks, such as the overlay/concrete interface, top/bottom rebars and slab bottom, the proposed model is much more comprehensive than a simple analysis of reflection amplitude at the top rebar layer. Moreover, the correlation coefficient method offers an absolute measure of attenuation of the GPR signal that, otherwise, cannot be obtained using the conventional amplitude analysis. For instance, if one is provided a GPR waveform from a single rebar location on a bridge deck to evaluate the severity of deterioration at the same location, it cannot be done with the traditional amplitude analysis. On the other hand, the same can be done easily using the proposed methodology. A more practical example would be a deck surveyed with a limited amount of collected GPR data. That data limitation would affect the reliability of choosing the reference amplitudes and the depth correction procedure, which is based on 90th percentile linear regression [5]. In addition, there is no guarantee that the rebars with the strongest amplitudes are in sound concrete. Naturally, for any deck, the entire deck area will deteriorate with time, but with different deterioration rates at different deck locations.

As another note, by analyzing full radar waveforms, some misinterpretations of the bridge deck condition can be avoided. For example, the reflection amplitude at a rebar location where there is moisture trapped underneath a waterproofing membrane may be low. While the amplitude analysis might suggest deterioration at that location, it will not be the case with the proposed methodology. The reason is that, because of a reflection from the moisture layer, the correlation coefficient will not be unity. Although the correlation coefficient in that case might be considered to make the condition assessment uncertain, it still indicates that EM energy is not completely lost when the wave is travelling from top deck to the moisture layer. In other words, the increased electrical conductivity (indication of deterioration) in the concrete cover in that case is not sufficient to absorb all EM energy.

A limitation of the proposed method is that the environmental/weather condition during the data collection may affect the results of GPR data analysis. As these factors may influence the strength of rebar reflection [13], different correlation coefficients may be obtained for the same bridge deck, if the data are collected during different seasonal and weather conditions. Their impact should be quantified in the future research. A simple solution to minimize the impact of those factors is to perform GPR surveys on bridge decks during stable weather conditions. Because of the relative nature of the conventional amplitude analysis, the analysis results obtained in that approach may be less affected by the seasonal and weather conditions, assuming that these factors would have a very similar impact on the rebar reflection amplitudes throughout the bridge deck area.

Through the creation of semi-simulated A-scans in this study, the need for baseline GPR data in the method developed earlier [10] can be eliminated. It is noted that, although using the same correlation coefficient between A-scans, the two analysis techniques employ different reference waveforms. Specifically [10], requires the reference GPR data to be collected when a bridge deck is in good condition, whereas the proposed methodology creates ideally-worst waveforms from a one-time GPR scan. As a consequence, while in the former approach the lower correlation coefficient indicates the more deteriorated concrete, the reverse is true with the proposed method.

Besides, it is noted that the method proposed by Dinh et al. [10] requires time-series GPR data to be collected strictly at the same locations over time to monitor deterioration progression on bridge decks, this is not the case with the proposed method. Although the positioning error can be minimized through using advanced navigation technologies, such as real-time kinematic and differential global-positioning systems [14], meeting the requirement would still be difficult when GPR data are collected manually. In addition, since most concrete bridge decks do not have baseline GPR data, the technique developed in this research is more ready for implementation.

Nonetheless, the main limitation of the proposed approach is that, compared with the conventional amplitude analysis, it requires higher computational effort. In addition, irregularities on the top surface of a concrete deck, such as potholes, surface debris or asphalt patches, may affect the shape of direct-coupling signal and amplitude at the top rebar. Therefore, the proposed method is limited to interpreting the condition at those deck locations. While this is also a limitation in the case of the conventional amplitude analysis, the creation of a separate semi-simulated waveform for each rebar location minimizes such effects. For instance, a pothole at a fully deteriorated location may distort the direct-coupling reflection and cause no reflection at the top rebar layer. By creating a semi-simulated waveform with the same section of distorted direct-coupling, the correlation coefficient at this location will still be unity and, therefore, the condition will be assessed correctly as a fully deteriorated concrete.

Although the proposed methodology has been validated through the three case studies, correlation coefficient thresholds should be investigated more in future studies. The purpose of the thresholds is to categorize bridge deck areas into different condition states according to the anticipated severity of deterioration. Since attenuation of GPR signal in concrete increases with the increasing frequency [15], the thresholds should be calibrated for different GPR equipment based on their corresponding center frequency. The higher the center frequency is, the higher the correlation thresholds will be. In addition, because GPR attenuation maps correlated well with other NDE techniques in this study, the threshold calibration can be performed in the future by comparing the results between the GPR and these technologies, for a larger group of bridge decks.

Finally, while the proposed technique is applicable to the air-coupled GPR, the application is anticipated to be less effective than for the ground-coupled GPR. The reason is that, in comparison to the direct-coupling (ground-coupled) reflection, the surface (air-coupled) reflection from the top of a deck tends to be more sensitive to the deterioration on the deck surface. Such sensitivity causes more uncertainty in assessing the deck condition with the proposed method. However, a correlation coefficient in such cases still provides an absolute indication of attenuation for the full deck thickness.

7. Conclusions

GPR signal attenuation is the most commonly used criterion to evaluate possible deterioration and damage in concrete bridge decks. However, because of a change in the best condition with time, such developed attenuation maps may not describe accurately deterioration of bridge decks. The model developed based on correlation of GPR A-scans can more independently and reliably assess the attenuation of ground-coupled GPR data and, thus, deck deterioration. This has been confirmed by correlations with results from other NDE techniques. In the future, the method should be further developed through investigation of threshold values of deterioration from comparisons with the results from other NDE technologies for a larger group of bridge decks.

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