Attenuation-based Methodology for Condition Assessment of Concrete Bridge Decks using GPR

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ABSTRACT

Reflection amplitude at top rebar layer has been used as a main criterion for evaluating attenuation of ground-penetrating radar (GPR) data from concrete bridge decks. However, a recent study has pointed out the limitation of this practice. Motivated by that same research, the current paper presents a robust method for performing GPR attenuation analysis. Also based on correlation between A-scans, however, instead of baseline data, semi-simulated waveforms are used in this approach. With only one reflection representing direct coupling, these waveforms mimic A-scans collected from completely damaged location. The output obtained is then plotted in form of a contour map of correlation coefficient in which higher value indicates more deteriorated concrete. As a validation, the method was implemented for two bare concrete bridge decks. The result indicates that while the maps provided by other technologies and GPR are geometrically correlated, in comparison with conventional amplitude analysis, the proposed model provides better vision on overall deterioration of bridge decks.

Keywords –

Ground Penetrating Radar (GPR), Concrete Bridge Decks, Bridge Inspection, Non-Destructive Evaluation (NDE).

1 Introduction

Ground-penetrating radar (GPR) is among the best technologies for condition assessment of concrete bridge decks [1]. As such, many procedures for analysing GPR data have been proposed and one of them has been adopted in an ASTM standard [2]. Nevertheless, Dinh et al. [3] found the limitation of the current practice. Specifically, instead of having an absolute measure of attenuation for entire A-scan at rebar location, the standard simply analyses the difference in reflection amplitude either at slab bottom or at top rebar layer. The condition at a specific location/rebar is then assessed based on the amplitude difference with the one that has strongest reflection. Suppose that this reference location/rebar also deteriorates over time that will most likely be the case, the overall deterioration of bridge deck will certainly be under-estimated. Such a problem will therefore be addressed in this research.

2 Research Objectives

Motivated by the above problem, the main goal of this study was to develop an analysis method that can better assess the attenuation of GPR data from concrete bridge decks. In order to achieve that goal, three research objectives were identified as follows:

(i) Understand GPR as a bridge deck condition assessment technique.

(ii) Study appropriate methodology for modelling attenuation of GPR signal.

(iii) Develop a procedure to map attenuation of entire bridge deck.

3 GPR for Condition Assessment of Bridge Decks

The deterioration of steel-reinforced concrete structures is a complex phenomenon that can be caused by the corrosion of steel or degradation of concrete. According to Gucunski et al. [1], rebar corrosion is among the four deterioration mechanisms those are of highest concerns to bridge engineers in the United States. Hence, detecting early signs of rebar corrosion is of highest interest during inspection of concrete bridge decks.

Brought in from geophysics application, GPR has been extensively studied for its capability in assessing condition of concrete structures, especially bridge decks.

Although Scott et al. [4] found that GPR is not a good tool for detecting hair-like delamination; it has been proved to be an effective technology for identifying concrete corrosion [1, 5, 6, 7, 8, and 9].

Based on propagation behaviour of electromagnetic wave, GPR data is very sensitive to corrosive environment (if any) in bridge decks. According to Tarussov et al. [8], when an EM wave passes through a conductive material, it will generate electrical currents in the material itself and the loss of energy caused by these currents will reduce the amplitude of the response. Therefore, for a bridge deck with varying corrosion severity, GPR signals tend to be attenuated more in the areas with increased chloride or corrosion.

To convert such a simple principle of GPR to bridge deck condition maps, many research works have been done in the literature. For example, Chung et al. [10] proposed using shape features of A-scan to analyse data of asphalt-covered reinforced concrete bridge deck collected with an elevated (horn) antenna. Using the same approach in addition to examination of amplitude, Barnes and Trottier [6] analysed 92 asphalt-covered concrete bridge decks in Nova Scotia in which the data was also collected by an air-coupled antenna.

Possibly, because visual analysis of individual radar waveform is somehow subjective and too time-consuming, it can only be found in some research papers and rarely practiced in the industry. To improve such situation and take advantage of the longitudinal information, Tarussov et al. [8] developed a new procedure to visually analyse B-scan (GPR profile). Justification for this was that B-scan provides more information and using it can speed up the analysis process. In addition, it was claimed that visual analysis of B-scan can eliminate amplitude anomalies those are caused by structural variation rather than corrosion-induced defects.

Still, the most commonly-used procedure to analyse GPR data from concrete bridge decks is the one guided by the ASTM standard [2]. Based on attenuation, the standard recommends that condition map can be developed using amplitude measured either at slab bottom or at top reinforcing mat. Concerning the latter method, although a threshold of -6 to -8 dB was written in the standard, these values are yet a research topic. Most recently, Dinh et al. [9] developed a model to determine flexible amplitude thresholds, based on K-means clustering technique. In another research, Martino et al. [11] tried to develop a threshold model based on the distribution features of depth-corrected amplitude.

While most studies have focused on condition assessment aspect of GPR, little effort were made to use this technology for condition monitoring. With a vision that in the future bridge decks would be monitored frequently using non-destructive technologies in general and GPR in particular, Dinh et al. [3] developed a method to analyse GPR time-series data. Based on correlation between A-scans, the method can be used to monitor change in corrosive environment in bridge deck, or to assess its condition if a baseline data exists for that same deck.

4 Research Methodology

As described above, while visual analysis methods consider shape features of either entire A- or B-scan, the ASTM standard only analyses a small piece of information extracted from GPR data. In the standard, the term "***attenuation***" is defined relatively as the amplitude difference between reinforcing bars. As can be imagined, in the ideal case where an entire bridge deck is corroded where all reflection amplitudes are week but not much different, the bridge would be misinterpreted as being in good shape. As such, in the following paragraphs, a methodology to model attenuation of a single A-scan is described and discussed.

The methodology was motivated by the observation in Fig. 1, for ground-coupled GPR. As can be seen, while reflection at top rebar mat and slab bottom are very sensitive to concrete corrosion, the first reflection, i.e., direct coupling, is much more stable. In addition, for more deteriorated concrete, reflection amplitude at top rebar and slab bottom reduce and tend to disappear in GPR image (B-scan). In the worst condition, there will be completely no reflection at these layers and A-scan will have only one reflection at deck surface (direct-coupling).

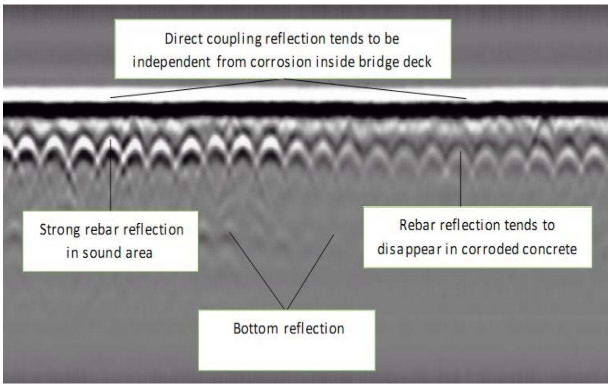


Figure 1. Model Motivation

As can be seen, the observation suggests a method to measure attenuation for a single radar waveform. Specifically, suppose that an A-scan has been collected at a rebar location as shown in blue colour in Fig. 2 and it needs to be evaluated for attenuation, the procedure is followed. First, a semi-simulated A-scan is created to mimic the one collected from completely damaged location. This A-scan, depicted by red colour in Fig. 2, has the same direct-coupling reflection as the original waveform, however, it does not have any reflection at other layers. Then the attenuation can be assessed by comparing the similarity between the two waveforms. Specifically, the more similar the two waveforms, the more attenuated the original A-scan.

Regarding comparison algorithm, it is recommended that the same correlation coefficient ρ_{xy} proposed by Dinh et al. [3] be utilized. As explained in Equation (1), ρ_{xy} is simply the normalized covariance between two digitized signals/variables *x(t)* and *y(t)*. Then, what can be said is, the closer to unity the coefficient, the more attenuated the original waveform. In addition, it is noted that, in order to be consistent for future research in calculating the coefficient and specifying coefficient threshold, this study suggests that only a 5-ns section of the signal be used for the model. As illustrated in Fig. 2, starting from direct-coupling, this section (about 0.5m of concrete) is enough to cover the thickness of most bridge decks.

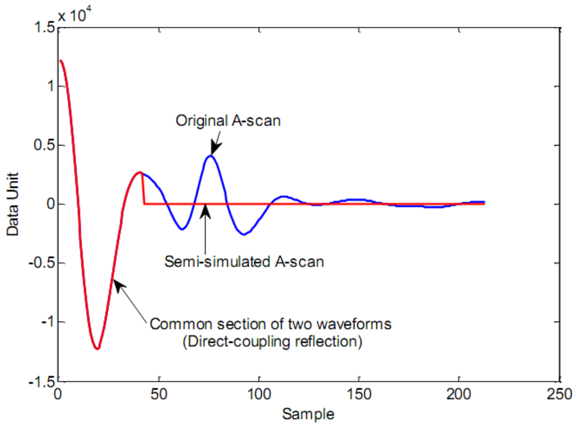


Figure 2. Comparison between original and semi-simulated waveform

$$\rho_{xy} = \frac{\gamma_{xy}}{\sigma_x \sigma_y} \qquad (1)$$

Where:

$\gamma_{xy} = E[(x_t - \mu_x)(y_t - \mu_y)]$

μ_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

To map attenuation for bridge decks, the conventional contour mapping is employed in this study. Written in MATLAB, a program has been developed to implement the entire process which is depicted in Fig. 3. As can be seen, first the program reads each GPR profile and processes to pick rebar location. This is done by using migration technique that focuses energy on true rebar location. The picking is then performed by searching pixel with high intensity along with additional picking criteria such as typical depth or migrated shapes of reinforcing bars. Although automation of rebar picking is not a topic of this paper, for the credibility of the model implementation, the accuracy of rebar picking was higher than 95 percent in this study. An example of a profile with picked rebars is provided in Fig. 4.

Once 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 comparison. For each pair of signals, correlation coefficient is computed by the program. All correlation coefficients and their corresponding location are then exported to a spread sheet to be read by a mapping software. The attenuation map is finally developed in the form of contour map of correlation coefficient.

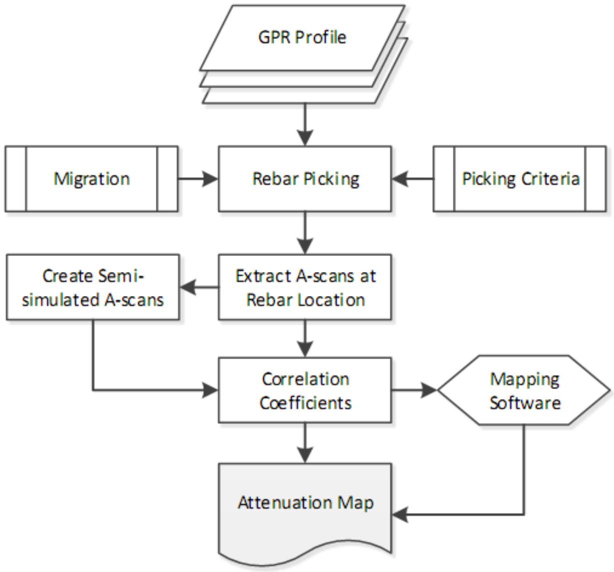


Figure 3. Procedure for mapping attenuation of bridge deck

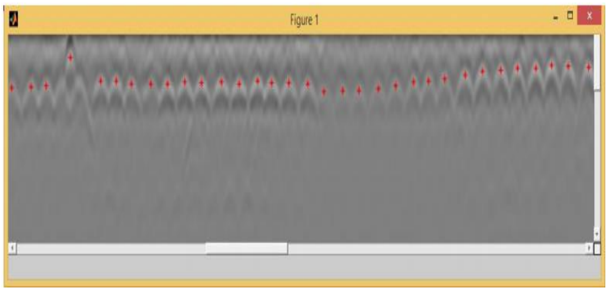


Figure 4. Example performance of rebar picking algorithm

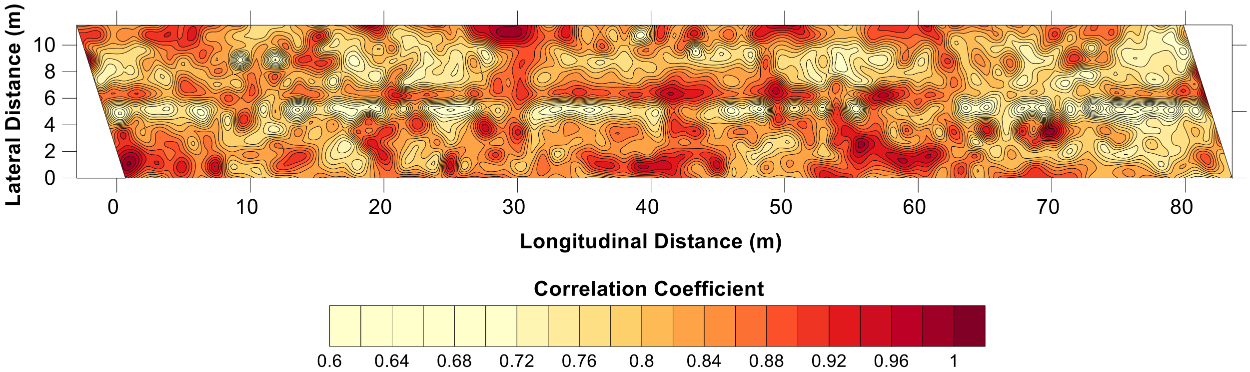
5 Case Study Implementation

In this section, the proposed methodology is implemented for two bare concrete bridge decks in the United States. Since in addition to GPR, the two decks were also surveyed by other NDE technologies, the maps provided by these techniques will be used to validate the proposed method.

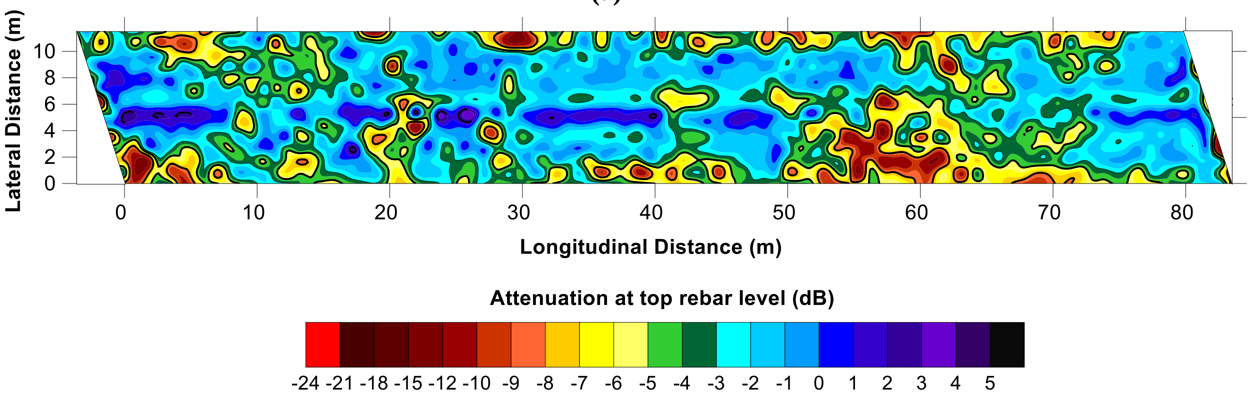
5.1 Haymarket Bridge, Virginia

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 deck is 22 cm in thick of reinforced concrete. The top mat of reinforcing bars is epoxy-coated whereas the bottom mat consists of bare bar reinforcement. 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).

For validation, the attenuation map created from the proposed model is first compared with the one developed using the ASTM methodology. As can be seen in Fig. 5, attenuated areas delineated in the two maps are very well correlated. The two maps are then further validated by comparison with other technologies depicted in Fig. 6. What can be drawn from these comparisons is that GPR correlates the best with ER test result. More specifically, the maps provided by GPR and ER look almost geometrically identical. This is reasonable since both two technologies are sensitive to conductive environment. In addition, the comparisons also indicate a good correlation between the maps provided by four technologies.



(a)



(b)

Figure 5. GPR attenuation maps for Haymarket bridge deck with (a) Proposed method and (b) ASTM standard

5.2 Pohatcong Bridge, New Jersey

Pohatcong Bridge in Warren County, New Jersey, was built in 1978 with a bare concrete slab resting on five steel girders. The bridge is 36 m long and 11 m wide with the deck thickness of 25 cm. The bridge was scanned in August 2014 using three different NDE technologies, namely GPR, ER, and IE. Condition maps were then generated for all techniques.

As the first case study, the attenuation map was developed from GPR data using both analysis techniques, i.e., the proposed method and ASTM standard. Depicted in Fig. 7, it is not difficult to realize that the more attenuated areas delineated by the two methods appear to be in the same locations. In addition, with the condition maps provided by other technologies illustrated in Fig. 8, again, the correlation between these technologies and GPR can be clearly observed. The best correlation can still be observed between GPR and ER test results.

6 Discussion

While the similarity between the maps observed in the case studies proved the validity of the proposed methodology, a huge difference between this technique and the conventional amplitude analysis should not be ignored. Specifically, if the ER maps of the two decks are examined at the same time, one can realize the corrosion rate of Pohatcong bridge deck is much higher. This is in line with the results provided by the proposed methodology when the average correlation coefficient of Pohatcong bridge deck is much higher than the one of Haymarket bridge deck, i.e., 0.9287 versus 0.8187. Ironically, as can be seen Fig. 9, ASTM amplitude analysis suggests lower attenuation for Pohatcong bridge deck. The average amplitude value for this deck is -2.41 dB whereas the value for Haymarket bridge deck is -3.13 dB.

The superiority of the proposed methodology can be explained due to the fact that it assesses the attenuation based on the entire A-scan. Scientifically, the model is a more comprehensive way to interpret amplitude data in which somehow reflection amplitude at top rebar is normalized by amplitude of direct-coupling. The similar result/effect can be obtained by using semi-simulated A-scan developed in this study.

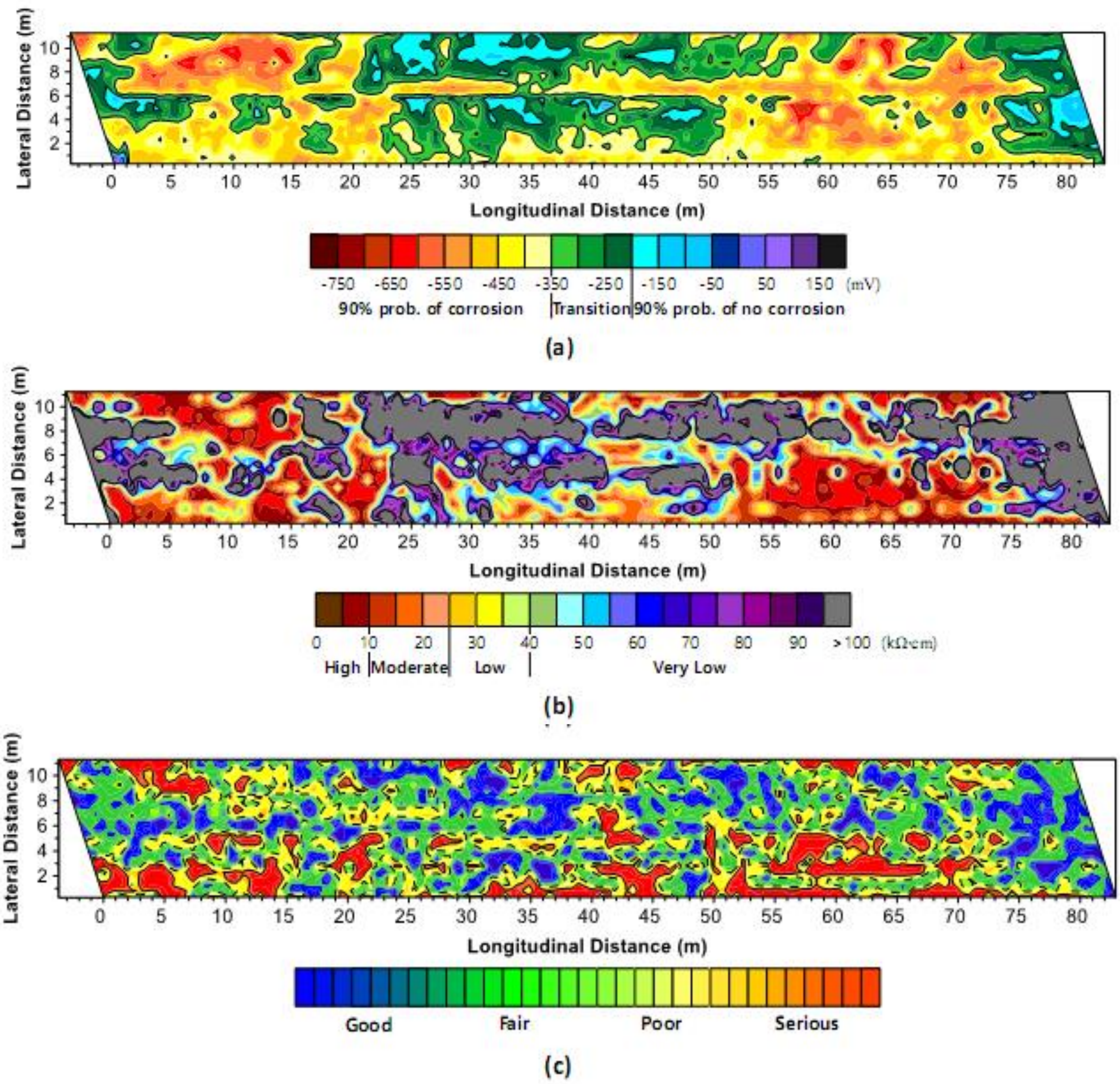


Figure 6. Condition maps for Haymarket bridge deck with (a) HP, (b) ER, and (c) IE.

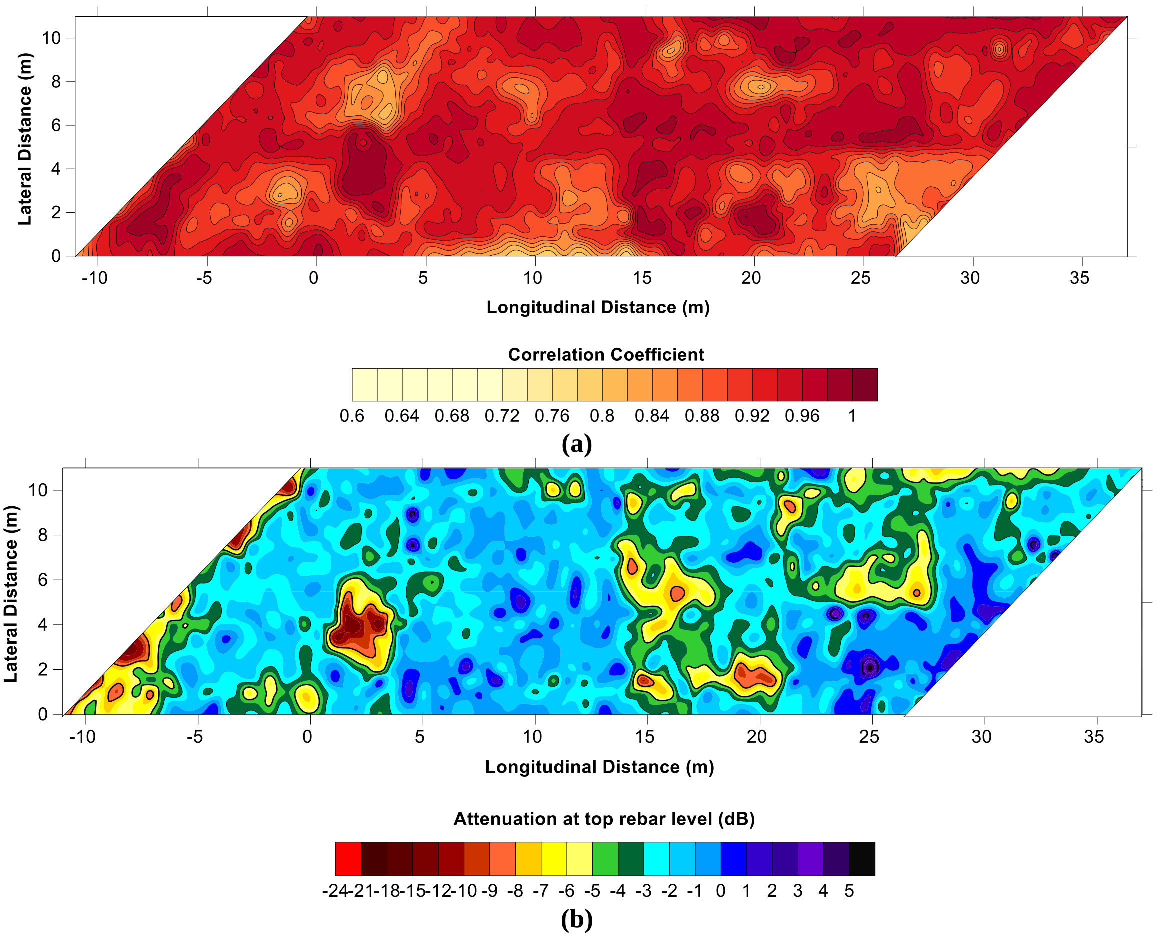


Figure 7. GPR attenuation maps for Pohatcong bridge deck with (a) Proposed method and (b) ASTM standard

In addition, by analysing full radar waveform, some misinterpretation can be avoided. For example, if reflection amplitude at a rebar location is low due to moisture trapped underneath waterproofing membrane, while amplitude analysis might suggest corrosion at that rebar, it will not be the case with the proposed methodology. The reason is that, because of a reflection from moisture layer, correlation coefficient will not be unity. In this regard, the methodology is more intelligent than simple amplitude picking.

As previously mentioned, a program has been developed in MATLAB to automatically implement the entire process proposed in this study. For each bridge deck, in addition a map of concrete cover, it generates condition maps using both the proposed technique and the traditional amplitude analysis. Since the current paper focuses on the attenuation model, description and explanation of the program will be addressed in a separate manuscript.

7 Conclusions

Attenuation has always been the criterion to evaluate GPR data from concrete bridge decks, however, currently the way it is defined is not appropriate. As a consequence, attenuation maps based on the definition do not reflect the true deterioration of bridge decks in this research. Based on correlation between A-scans, the model developed in this study can better assess the attenuation of GPR data and this has been confirmed by the maps collected with other NDE techniques. Certainly, the model would be of interest to transportation agencies in North America where corrosion of rebar is the leading cause for rehabilitation of concrete bridge decks.

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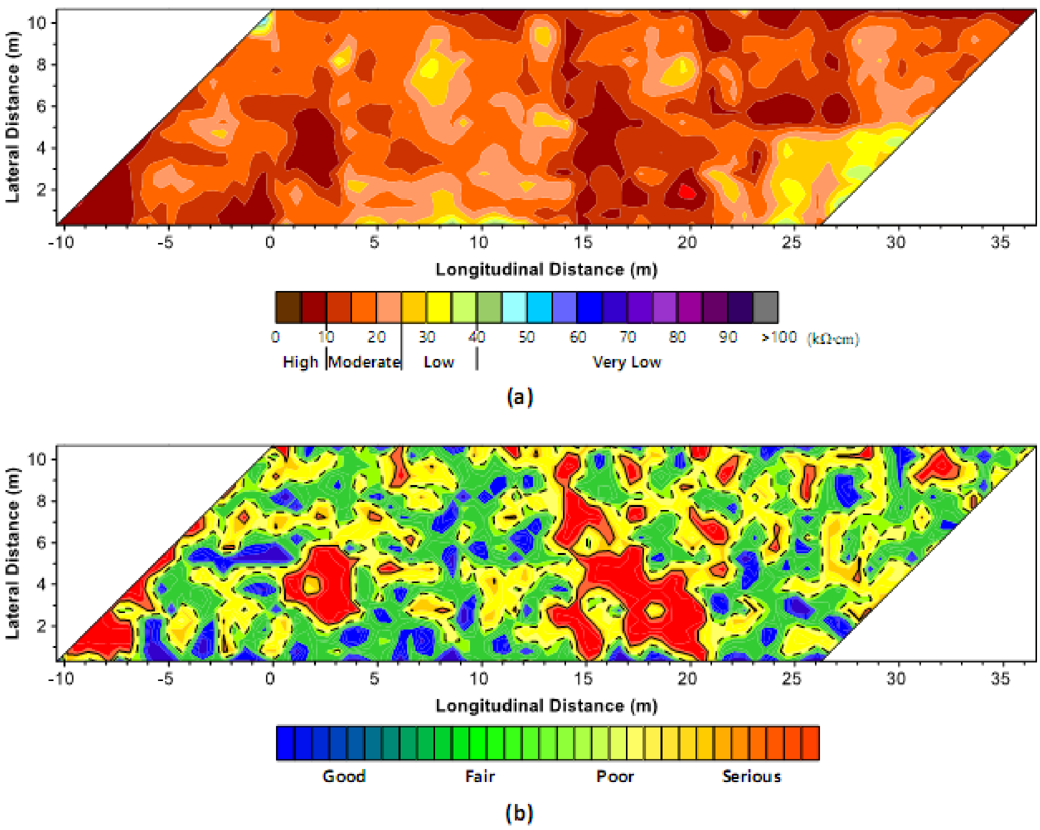

Figure 8. Condition maps for Pohatcong bridge deck with (a) ER, and (b) IE

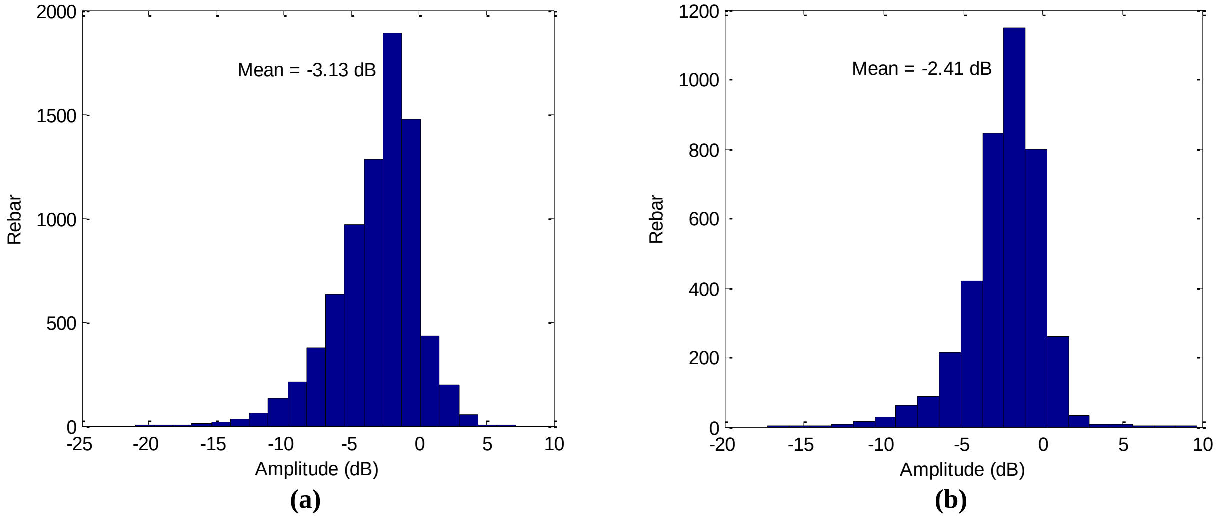

Figure 9. Histogram of depth-corrected amplitude for (a) Haymarket bridge deck and (b) Pohatcong bridge deck.

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