PART 4

Field Testing and Nondestructive Evaluation of Transportation Structures

Clustering-Based Threshold Model for Condition Assessment of Concrete Bridge Decks with Ground-Penetrating Radar

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Ground-penetrating radar (GPR) has been extensively studied for condition assessment of concrete bridge decks in North America. Although several methods for analyzing GPR data have been proposed, the commonly accepted method evaluates the condition of concrete bridge decks on the basis of the difference between reflection amplitudes of the top rebar layer. It is assumed in the method that strong reflection indicates sound concrete, whereas the area with high-amplitude attenuation is associated with concrete corrosion. The final result is a contour map of reflection amplitude in decibel scale with the thresholds selected arbitrarily to define the severity of concrete deterioration. Because subjective determination of threshold values may lead to inconsistency in the result obtained, this paper proposes a robust method for resolving that issue. Specifically, after depth correction was performed for top rebar amplitudes, on the basis of *K*-means clustering technique these amplitude data were grouped into a number of condition categories. Through two case studies in North America, the methodology was implemented and compared with the results provided by other technologies, namely, concrete resistivity, half-cell potential, and laboratory chloride content analysis. The implementation showed that while the proposed method was simple to employ, it still provided reasonable results that were in line with the outputs provided by the other techniques.

Highway bridge structures play a critical role in transportation system. Consequences of highway bridge failure are usually catastrophic, for both human life and economic loss. While one-third of Canada's 75,000 highway bridges have structural or functional deficiencies and a short remaining service life (*1*) as of December 2013, more than 100 million square meters of the total 360 million square meters of concrete bridge decks in the United States are either structurally deficient or functionally obsolete, according to FHWA (*2*). The American Society of Civil Engineers estimated that an annual investment of $20.5 billion would be needed to eliminate the nation's bridge deficient backlog by 2028 (*3*). The largest portion of this expected expenditure is allocated to bridge decks (*4*).

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

Another problem with the visual inspection method is that it provides subjective information that in turn affects the quality of bridge maintenance decision making. In 2001, FHWA conducted comprehensive research to evaluate the reliability of the visual inspection method in the United States (*5*). One of the main findings of that research is concerned with the accuracy of visual inspection results. It was reported that on average there were between four and five different condition rating values assigned to each primary element, while the overall scale is from 0 to 9. It was also stated that at least 48% of the individual condition ratings for the primary elements were assigned incorrectly.

To overcome the limitations of visual inspection, various nondestructive evaluation technologies have been studied by both the industry and the research community. Among these technologies, ground-penetrating radar (GPR) has been considered for many years as a highly promising technique. However, despite many advancements in the hardware configuration, the technology is still in limited practice (*6*).

RESEARCH OBJECTIVES

The main goal of the present research is to study a robust method for determining threshold values when one analyzes GPR data of concrete bridge decks with the use of conventional amplitude analysis. To achieve that goal, the following objectives must be met:

1. Understand the working principles of GPR,
2. Study available approaches for analyzing GPR data, and
3. Develop a method for determining threshold values.

BACKGROUND

GPR is a detection technique that was adapted for civil engineering application from the geophysics discipline. This technology detects subsurface objects or defects on the basis of the principle of electromagnetic wave propagation. When a beam of electromagnetic 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. The intensity of reflected energy is dependent on the intensity of incident energy at the interface and the relative dielectric constants of the two media. Therefore, by sending a wavelet and analyzing the received waveforms, anomalies or objects in the structure can be identified. In the literature, available methods for performing the analysis are as follows.

Numerical Analysis of Reflection Amplitude

Numerical analysis of reflection amplitude is a technique for analyzing GPR data on the basis of the amplitudes measured at various material interfaces. This technique is the most commonly used one for evaluating GPR data of concrete slabs. Although the reflection amplitude at the concrete surface, bottom rebar, or slab bottom may be taken into account, most often the analyst will infer the condition of bridge deck on the basis of the reflection amplitude at the top reinforcing bar. The rationale behind this evaluation method is based on known effects of moisture, chloride content, and rust on the recorded GPR signals. These effects are described in detail by Tarussov et al. (*7*). In short, they cause more attenuation on reflection amplitude.

According to Barnes et al., rebar depth may affect the amplitude measured instead of concrete deterioration (*8*). They found that when normalized reflection amplitude for a concrete deck was plotted against two-way travel time, a general decreasing linear trend was observed. On the basis of this observation, for depth correction they proposed that a quantile linear regression fitting was performed at the 90th percentile. This regression line was then used for depth normalization by subtracting it from the depth-dependent amplitude. The next step to produce an amplitude map would be the same as in the conventional amplitude method.

As for the threshold to differentiate between deteriorated concrete and a sound area, common practice has been that the threshold values are selected arbitrarily on the basis of the analyst's experience. Recently, Martino et al. proposed a statistical model for threshold calibration in which GPR data were correlated with half-cell potential (HCP) (*9*). The purpose of the model was to use GPR as a sole tool to assess the corrosion state of bridge decks. Specifically, their model development was motivated by the observation that for a healthy bridge deck, the amplitude histogram was compact, quite symmetric, and almost perfectly normal, while the histogram for a corroded bridge deck was spread out and leaning to one side. For a library of eight bridge decks with HCP results, they then explored various descriptive statistics for prediction purposes, such as mean, standard deviation, variance, skewness, and kurtosis. On the basis of that exploration, they came up with a linear regression formula to calculate corrosion area in which they concluded that the product of skew and mean value of GPR amplitude data provided the best prediction performance. Finally, with corroded area percentage obtained, the GPR threshold can be found through an interactive trial-and-error process.

Visual Interpretation of GPR Data

Visual interpretation of GPR data refers to those techniques that are based on visual recognition of deterioration in GPR data. For example, Chung et al. developed a technique for evaluating GPR data of an asphalt-covered reinforced concrete bridge deck collected with an elevated (horn) antenna (*10*). The method is based on the characteristic W-shape of individual GPR signals in which any variation from this W-shape characteristic is considered to indicate some signs of deterioration.

Also on the basis of visual analysis of individual radar waveforms, Barnes and Trottier investigated the effectiveness of GPR to forecast repair quantities for concrete bridge decks (*11*). The research reported a varying range of forecast accuracy. Specifically, it was concluded that the method seems to work well when the decks exhibit 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 show significant differences between the GPR and ground-truth survey quantities.

Because visual analysis of individual waveforms is very time-consuming and impractical to be used in bridge deck inspection, Tarussov et al. proposed a new procedure for mapping corrosion in concrete structures, based on line scan (B-scan) image analysis (*7*). To analyze GPR data for a concrete bridge deck, the analyst scrolls through each GPR profile and marks visible anomalies on the basis of known criteria of deterioration. The processed profiles are then combined by a specialized software tool to generate a corrosion map.

One challenge facing the analyst in some instances when he or she visually analyzes GPR profiles is that it may be difficult for him or her to define clearly the border between sound and deteriorated areas. Also, it is very hard for the analysts to keep their judgment consistently between themselves, when they switch between profiles or when they have to separate the analysis time because of management issue. In other words, visual interpretation of GPR profiles is also subjective to a certain extent. Different data interpreters may come up with different condition maps. Obviously, this subjectivity effect is not desired and therefore should be minimized.

Correlation Analysis of Time Series GPR Data

Correlation analysis is a method recently proposed in the literature for analyzing time series GPR data (*12*). Basically, it assesses bridge deck deterioration by analyzing the change of GPR signals over time. The analysis is done by computing the correlation coefficient between A-scans (new one versus baseline) with the assumption that the more similarity there is between the two signals, the better the quality of the concrete, at a specific location. After correlation coefficients have been obtained, a contour map of correlation coefficients will be plotted for the entire deck. This map would be the condition map of the deck because the areas with low correlation coefficients will correspond to the regions with the corroded rebars.

By taking into consideration two important pieces of information, both the amplitude and the shape of an individual signal, correlation analysis is much more comprehensive than simply comparing top rebar amplitude or visual interpretation of GPR data. However, since the method requires historical (baseline) data, it is not yet suitable to be practiced by the industry when usually only one GPR data set is collected for one bridge at inspection time. Although the need for the baseline signals using this methodology can be eliminated or replaced by a library of healthy GPR signals, such a library should be carefully prepared and collected to cover different types of bridge decks already in operation in North America.

METHODOLOGY AND MODEL DEVELOPMENT

Given the above situation on time series data, analyzing GPR data of concrete bridge decks on the basis of top rebar reflection amplitude is still the most preferable strategy. Since one of the main questions that have to be answered with this analysis method concerns threshold values, it is the topic of interest in this study. Before delving into the details of the methodology, *K*-means clustering, the employed technique, is explained below.

K-Means Clustering Technique

K-means clustering is a partitioning technique that was independently discovered in various scientific fields by Steinhaus (*13*), Lloyd (*14*), Ball and Hall (*15*), and MacQueen (*16*). As the most commonly used method for cluster analysis, the *K*-means procedure divides *N*-dimensional population into *K* sets such that the squared error between the empirical mean of a cluster and the points in the cluster is minimized (*17*). According to Jain, data clustering has been used for three main purposes: (*a*) to gain insight into data, generate hypotheses, detect anomalies, and identify salient features; (*b*) to identify the degree of similarity among forms or organisms; and (*c*) as a method for organizing the data and summarizing it through cluster prototypes (*17*).

In the computation algorithm, *K*-means clustering proceeds by randomly selecting *K* initial cluster centers (c_j) and then iteratively refining them according to the two following steps (*18*):

1. Each data point is assigned to the data set associated with the nearest centroid where the Euclidean distance between the data point x_i and the centroid c_j of cluster j is calculated with Equation 1.
2. Each cluster center c_j is updated to be the mean of its constituent data points.

The two steps are repeated until the centroids and data points no longer move; the clustering process stops.

$$d(x_i, c_j) = \left(\sum_{d=1}^{D} |x_{id} - c_{jd}| \right)^{1/2} \tag{1}$$

where

x_i = data point i,
c_j = centroid of cluster j,
d = dth dimension, and
D = dimension of the data needed to be classified.

Clustering-Based Threshold Calibration

As can be seen from the literature, although amplitude analysis provides an objective and detailed map in decibel scale that is useful for relatively comparing corrosion severity between rebars, the bridge maintenance planner needs more conclusive information as to which concrete should be removed and replaced during bridge deck repair. Conventional practice has been that the analyst selects the threshold values on the basis of his or her experience. However, although visual interpretation of the GPR data described in Tarussov et al. (*7*) may provide a condition map with specific condition categories that is useful for the bridge maintenance planner, the determination of the condition boundary is subjective as well. To eliminate the subjectivity of both analysis methods, an enhanced technique is proposed in this study. The basic idea is that while a detailed attenuation map in decibel scale can be used to determine the relative level of corrosion between rebars, bridge deck age and information gained from visual analysis of GPR profiles will be used to determine the number of condition categories (*k*).

As illustrated in Figure 1, the proposed method works as follows. Once the amplitude data have been obtained for all rebar picks through the conventional process of amplitude analysis with the depth correction described previously, the analysts will ask themselves, how many condition categories (*K*) would be appropriate to describe the condition of the bridge deck being considered? This question should be answered by analyzing bridge deck age information as well as visual analysis of GPR profiles through a process depicted in Figure 2. Then, the amplitude data will be grouped into that same number of clusters by *K*-means clustering, the most commonly used clustering technique described above. On the basis of the result of clustering, the threshold value for each condition category will be determined and the corrosion map will be plotted. For convenience, except rebar picking and visual examination tasks that are performed with specialized GPR software, other analysis steps have been automated in a program written by the first author. The final output of the program is an Excel file containing amplitude information and the threshold values for mapping bridge deck corrosion.

Unlike the well-accepted amplitude analysis, justification is needed for using visual examination in the proposed methodology. One may think that it makes the analysis unnecessarily

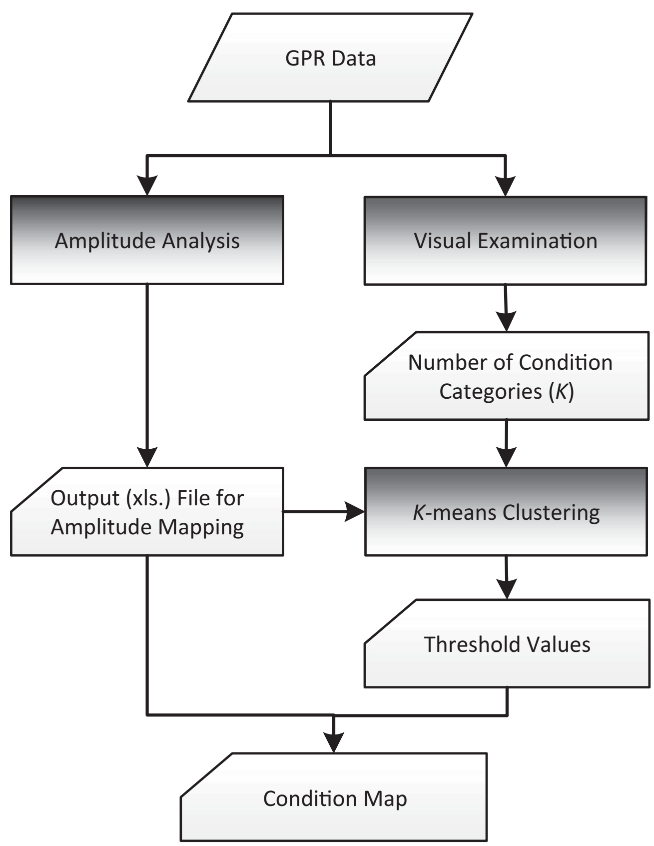

FIGURE 1 Analysis of work flow for proposed methodology.

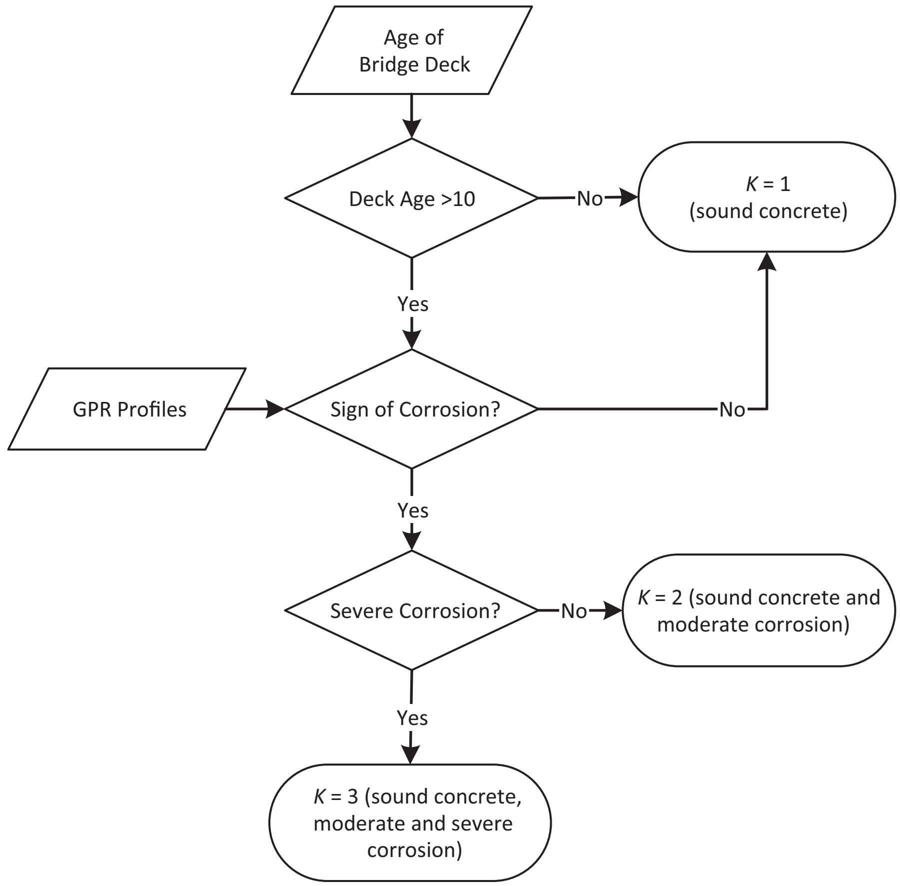

FIGURE 2 Flowchart for determining number of condition categories (*K*).

time-consuming, but it does not. Even when amplitude analysis is employed, an expert analyst is still required for quality assurance and he or she has to review manually picked or processed rebar amplitude data. The purpose is to guarantee that amplitude change is not caused by real construction variations either designed or built into the deck. In addition, by looking at GPR profiles, an experienced analyst can usually extract a lot of information about bridge deck condition, such as increased moisture, corrosion (*7*), and sometimes delamination (*19*). The only problem with this analysis method is that the determination of condition boundaries is somewhat arbitrary.

Justification also exists when bridge deck age information is used for determining the number of clusters. Specifically, for a new bridge deck, Martino et al. reported a standard deviation of 1.537 dB for the amplitude data and the difference between rebar reflection amplitudes was up to 12 dB (*9*). While the condition of that bridge deck may be misinterpreted if only a contour map of the reflection amplitude is analyzed, this will not be the case if the analyst knows the deck is new before he or she analyzes the data. In such cases, the analyst has enough information to conclude that the amplitude variation is caused by other random factors, rather than by corrosion-induced deterioration.

Concerning the deck age decision point in Figure 2, the study conducted by Kirkpatrick et al. pointed out that the time for chloride to reach and initiate corrosion varies greatly between bridge decks, depending on various factors (*20*). Although for some bridges it may take only 10 years for corrosion to be initiated, in most cases this time is up to more than 30 years (*20–23*). The selected 10-year decision point therefore can be justified when, on the basis of the studies mentioned above, it is very unlikely that corrosion initiates in bridge decks that are under 10 years of age.

CASE STUDY AND MODEL IMPLEMENTATION

In this section, the proposed methodology is implemented for two case studies: (*a*) a bare concrete bridge deck in New Jersey and (*b*) an asphalt-covered concrete bridge deck in Quebec, Canada. Each of them is described in turn as follows.

Pohatcong Bridge, New Jersey

Pohatcong Bridge in Warren County, New Jersey, was built in 1978 with a bare concrete slab. The bridge deck was tested in 2012 by Rutgers University using a ground-coupled radar system along with concrete resistivity. To analyze the GPR data with the proposed methodology, conventional amplitude analysis is performed first. Specifically, after rebar picking is done in the specialized GPR software, depth correction is carried out in the program previously mentioned. The number of condition categories (*K*) is then determined on the basis of the bridge deck age along with visual examination

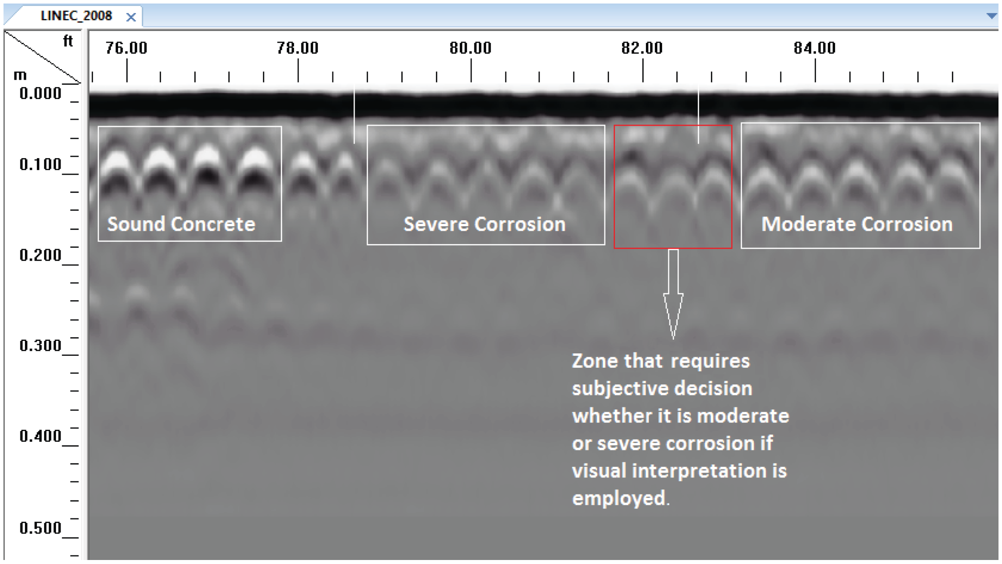

FIGURE 3 Visual examination of GPR profiles.

of all GPR profiles. For the deck being considered, with more than 30 years in service, it is reasonable to predict that certain rebar corrosion has initiated in the concrete. This assumption is verified by visual analysis of GPR profiles, an example of which is illustrated in Figure 3.

As can be seen, although expert analysts can easily realize three levels of concrete deterioration (sound concrete, moderate corrosion, and severe corrosion), a problem arises with boundary determination when there is no clearly defined criteria for them to do so. With the proposed method, only the number of condition categories (i.e., $K = 3$) is used for automatically grouping amplitude data. The clustering result (the threshold and area percentage of each condition category) obtained from the program is shown in Figure 4, and the corrosion map based on these thresholds is depicted in Figure 5*a*.

To validate the proposed methodology, the map in Figure 5*a* is compared with the map provided by the concrete resistivity test shown in Figure 5*b*. As can be seen, because the two technologies are based on the same parameter (i.e., electrical conductivity of concrete), they provide considerably similar results. Specifically, yellow and red areas in Figure 5*a* tend to correlate with the regions in Figure 5*b* where corrosion rates are indicated as either high or very high (electrical resistivity lower than 10 kohm * cm).

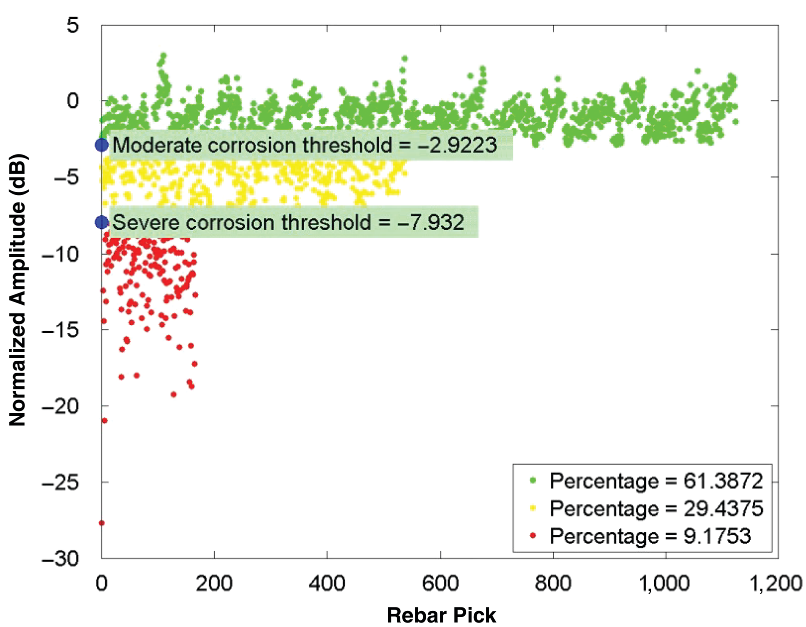

FIGURE 4 Clustering result for amplitude data.

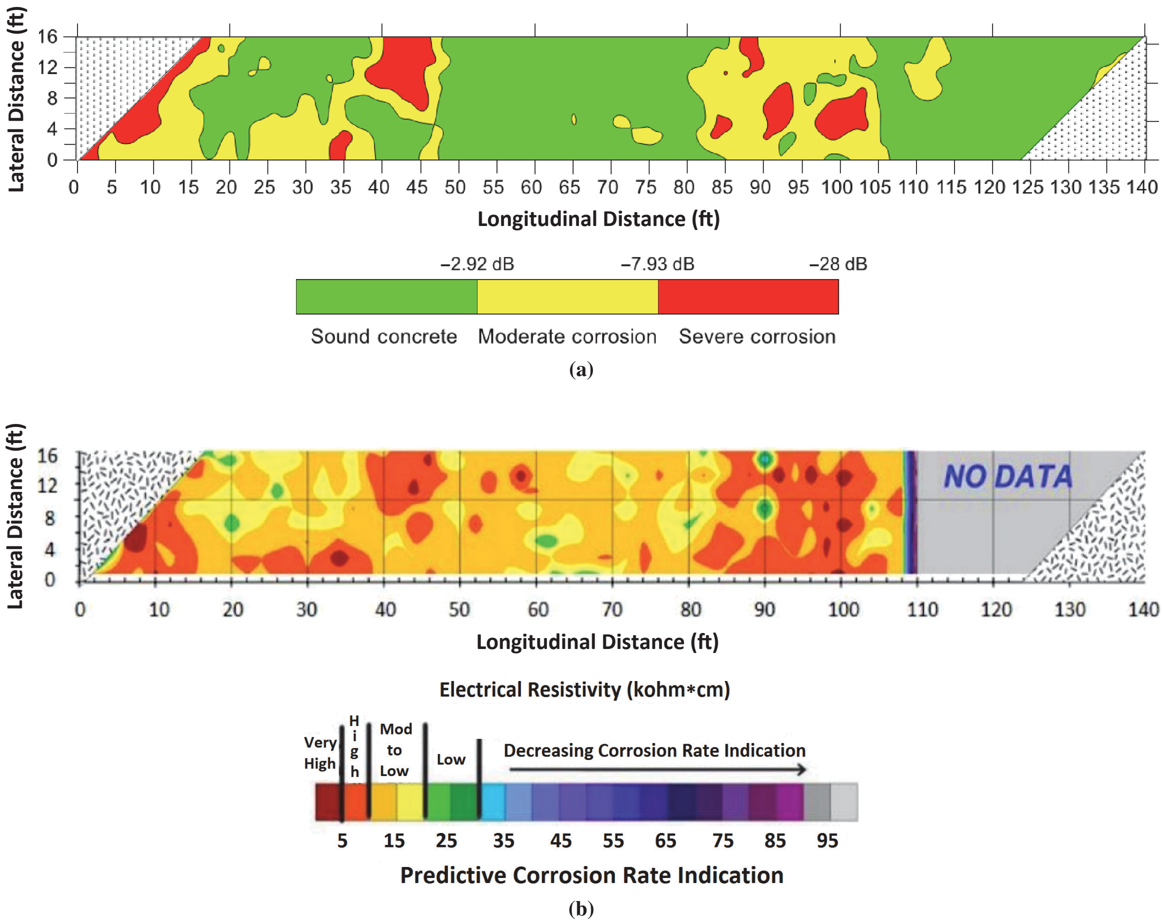

FIGURE 5 Corrosion maps based on (*a*) proposed threshold model and (*b*) concrete resistivity.

Bridge X, Quebec, Canada

Bridge X, located in Laval, Quebec, Canada, was built in 1966. It consisted of a 1-ft reinforced concrete deck with asphalt overlay that rested on five I-shaped steel girders. With apparent damages that could be seen from the slab bottom, both nondestructive and destructive tests were performed on the deck before it was demolished and replaced in 2014. Specifically, the first test performed on the bridge deck was GPR in which the data were processed with the methodology developed in this study. The GPR system employed for the test was the same as in the first case study, and the analysis result is shown in Figure 6*a*.

As in the first case study, to validate the GPR analysis result, it was decided that additional tests would be performed, namely, (*a*) hammer sounding to detect delamination, (*b*) HCP for corrosion mapping, and (*c*) core drilling of concrete samples for visual and laboratory chloride content analysis. Through a consulting contract, all the tests were done by a large soil, materials, and environmental engineering consulting group in Canada. While the cores and their corresponding locations are indicated by big dots in Figure 6, the result provided by each test is described in turn as follows.

According to the demolition schedule, the pavement was removed at the two ends of the slab and a delamination survey was performed for only these limited areas. Since some concrete cover in delaminated areas was attached to the asphalt layer during the removal, delamination and even exposed rebars could be seen in these special regions. In addition, by using the hammer sounding technique, invisible delaminations were detected; the final delamination result is plotted in Figure 6*b*. As can be clearly seen, although there are some considerable overlaps between delaminated areas with the red regions in Figure 6*a,* this mapping is an incomplete validation of the method. Previous experiments have shown that not all delamination can be observed in GPR images (*19*).

Figure 6*c* shows the result with the HCP test, which indicates that corrosion had initiated in almost the entire deck area and most of these areas were in advanced or highly advanced stages. Concerning geometry, the black (highly advanced corrosion activity) regions on the map correlate well with the yellow and red areas in Figure 6*a.* What can be said is, in comparison with the HCP method, the GPR analysis tends to delineate highly advanced corrosion areas with more detail, while the regions where corrosion is active or advanced would all be considered to be sound concrete. This remark should be carefully verified by visual inspection of core samples and laboratory analysis of chloride content before any conclusion can be made.

Although 10 core samples were taken for visual inspection, only four of them (Numbers 5 to 8) were tested for chloride content. The analysis result is summarized in Table 1. While the proposed methodology differentiates well uncorroded (Core 5) from corroded rebar (Cores 4, 7C, and 8), the HCP method tends not to recognize this difference. On the basis of this result, it is suggested that moderate

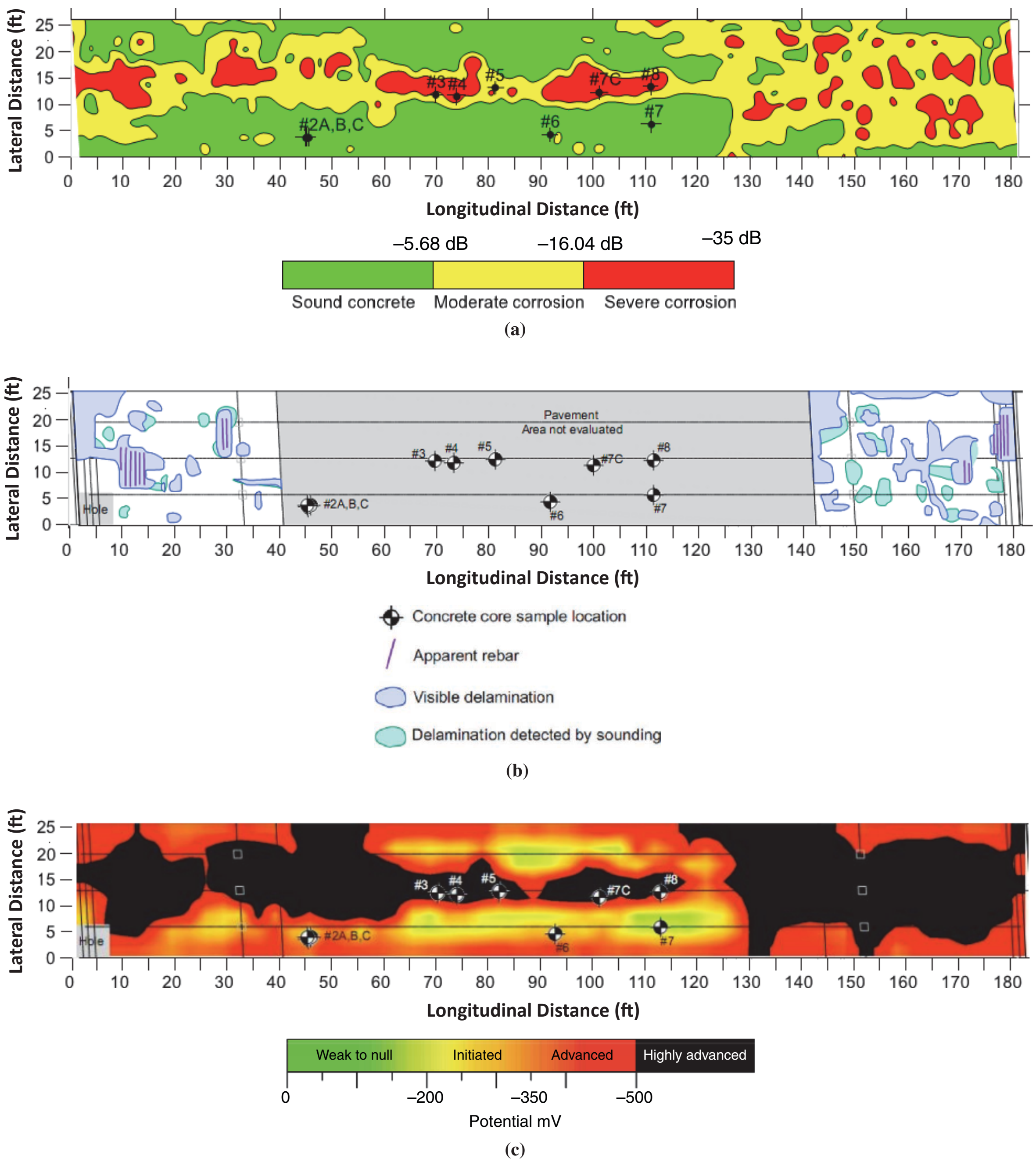

FIGURE 6 Condition maps provided by (*a*) proposed threshold model, (*b*) delamination testing, and (*c*) half-cell potential.

TABLE 1 Visual and Chloride Analysis of Core Samples

Core Number	Chloride Ion Content (% mass of concrete) At 0–20 mm	At 30–50 mm	At 60–80 mm	Delamination	Rebar condition
2A	—	—	—	No	Uncorroded
2B	—	—	—	No	—
2C	—	—	—	No	—
3	—	—	—	No	—
4	—	—	—	No	Corroded
5	0.310	0.271	0.155	No	Uncorroded
6	0.037	0.040	0.049	No	—
7	0.124	0.136	0.091	No	Uncorroded
7C	—	—	—	No	Corroded
8	0.567	0.338	—	Yes	Corroded

NOTE: — = data not available.

corrosion (yellow area) delineated by the proposed method should be interpreted as the area in which the corrosion process is initiated but rust formation is not likely. For the chloride content analysis, Table 1 suggests that for all four core samples being studied, the chloride concentrations were detrimental to concrete when, with regard to concrete mass, all of them were greater than 0.025%, the commonly accepted chloride threshold that facilitates rebar corrosion (*24*).

DISCUSSION OF RESULTS

The two case studies described in this paper clearly illustrate the implementation of the proposed methodology. As can be seen, in comparison with the conventional amplitude method, two additional steps are involved in the analysis: (*a*) visual examination of GPR profiles and (*b*) *K*-means clustering. Although the two bridges investigated are quite old with considerable areas of severe corrosion, the method can certainly be implemented in the same manner as for bridge decks that are subject to only moderate corrosion. Since deck maintenance is more effective the earlier the concrete corrosion is detected and treated, this type of bridge deck will be targeted in future studies.

For the bridge deck in Canada, since no delamination or corrosion was observed in Core 5 whereas the chloride level at the top rebar layer has passed the commonly accepted threshold, some discussion is provided for this issue. Although 0.025% weight of concrete mass is usually considered in the United States as the chloride threshold (*25*), according to Glass and Buenfeld (*24*), the true threshold level varies extensively. Specifically, on the basis of the study of literature, Glass and Buenfeld reported a range from 0.17% to 2.5%, with regard to cement weight, for the chloride threshold. If a cement content of 350 kg/m^3 and a sample density of 2,300 kg/m^3 are assumed as in Glass and Buenfeld (*24*), this range would be correspondingly from 0.026% to 0.38%, with regard to concrete mass. These numbers indicate that the chloride data obtained in the research are reasonable, in light of previous studies.

CONCLUSIONS

Based on the results of the two case studies, some important notes and conclusions can be summarized as follows. First, GPR and the threshold model proposed in this study provided reasonable results that were in line with the output produced by other test methods, such as concrete resistivity and half-cell potential. Second, although the delamination result was used as a partial validation for the proposed methodology, GPR should not be considered as a technique to directly detect this type of flaw. Third, the proposed method is only appropriate for detecting concrete corrosion; it should not be used to recommend bridge deck repair based on chloride contamination. For this purpose, the HCP method and chloride laboratory testing should provide more informative results. Finally, the proposed method is very simple to implement. It facilitates the automation of GPR data analysis and eliminates the subjectivity associated with the traditional method for threshold selection. The output of the method proposed is used to calculate the bridge deck corrosiveness index that will help transportation agencies to identify critical deficiencies and focus limited funding on the most deserving bridge decks. This topic will be described and discussed in another paper.

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