Method for Analyzing Time-Series GPR Data of Concrete Bridge Decks

Kien Dinh[1]; Tarek Zayed, M.ASCE[2]; Francisco Romero[3]; and Alexander Tarussov[4]

Abstract: Ground-penetrating radar (GPR) has been extensively studied in North America as a nondestructive evaluation (NDE) technology for inspection of concrete bridge decks. With current practices, however, GPR has only proven to be an indicator of potential damage. Basically, to obtain the condition map for a concrete bridge deck, one would try to analyze one-time GPR data based mostly on the relative difference between reflection amplitudes at the top rebar layer. With a hypothesis that time-series GPR data can provide better information on bridge deck deterioration progression, this study investigates and proposes a new method to interpret those time-series data sets. Based on a correlation coefficient between A-scans, the proposed methodology was implemented and validated for a bare concrete bridge deck in New Jersey. The map provided by the proposed method clearly shows deterioration progression between the two consecutive scans, whereas the traditional analysis technique using the top rebar amplitude suggests unreasonable improvement of the deck condition over time. **DOI: 10.1061/(ASCE)BE.1943-5592.0000679.**

Author keywords: Ground-penetrating radar (GPR); Nondestructive testings; Concrete bridge decks; Bridge inspection.

Introduction

Ground-penetrating radar (GPR) is an object-detection technique that is based on the propagation behavior of electromagnetic (EM) waves. When a beam of EM energy encounters an interface between two media of different dielectric constants, a portion of energy is reflected back, while the remainder penetrates through the interface into the next medium. By recording and analyzing these reflection waveforms, the presence of various material layers or structural defects can be identified and detected.

To inspect a structure such as pavement, a parking garage, or a bridge deck, an antenna is dragged manually by using a pushcart or by attaching it to another vehicle. This antenna transmits a short pulse of EM energy into the surveyed structure. The energy reflected at various material interfaces is received by another antenna (bistatic mode), or sometimes by the same antenna (monostatic mode), to produce the output signal (A-scan) that is proportional to the amplitude of the reflected EM field. This process is repeated at a certain pulse repetition frequency, typically 100 kHz, as the antenna is moved along the survey path. The output is usually presented as a grayscale image (GPR profile or B-scan), as shown in Fig. 1.

As a nondestructive evaluation (NDE) technology, GPR is considered a good technique for concrete bridge deck inspection. Theoretically, this technology can detect common defects in concrete bridge decks, such as corrosion and delamination, with high speed and precision of data collection. Even a standard test method has been issued by ASTM, providing guidelines for evaluating asphalt-covered concrete bridge decks using GPR radar (ASTM 2008). However, due to several reasons pointed out by Tarussov et al. (2013), this standard does not consistently provide acceptable results. As a consequence, GPR output based on the standard has proven to be only an indicator of potential damage.

In addition to the aforementioned struggles with the ASTM standard, the current data interpretation method is limited due to the fact that it is based on the relative difference in reflection amplitudes from one scan time. To overcome this limitation, the authors hypothesize that an analysis of time-series GPR data (data collected at different points in time for the same structure) should be performed. Specifically, it is assumed that, by studying the change of GPR signals over time, long-term performance of concrete bridge decks can be monitored and better assessed than by using the current data analysis method. This idea is also made possible when more and more GPR data sets become available through industry practices, as well as university research projects.

[1]Ph.D. Candidate, Dept. of Building, Civil, and Environmental Engineering, Concordia Univ., Montréal, QC, Canada H3G 1M7 (corresponding author). E-mail: dinhkien_huce@yahoo.com

[2]Professor, Dept. of Building, Civil, and Environmental Engineering, Concordia Univ., Montréal, QC Canada H3G 2W1. E-mail: zayed@encs.concordia.ca

[3]President/Owner, Romero NDT & E, 134 Hockenbury Dr., Glen Gardner, NJ 08826. E-mail: romero60@comcast.net

[4]President, Radex Detection, Inc., 353 St-Nicolas, Ste. 001, Montréal, QC, Canada H2Y 2P1. E-mail: alex@radarexpert.ca

Note. This manuscript was submitted on October 29, 2013; approved on July 21, 2014; published online on August 11, 2014. Discussion period open until January 11, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Bridge Engineering***, © ASCE, ISSN 1084-0702/04014086(8)/$25.00.

Research Objectives

The main goal of the current research is to develop a time-series analysis method for GPR data of concrete bridge decks. To achieve that goal, the following objectives are obtained:

1. Study amplitude method as the most commonly used technique for GPR data interpretation;
2. Investigate the applicability of the amplitude method for analyzing time-series GPR data; and
3. Develop a new method for interpreting time-series GPR data of concrete bridge decks.

Amplitude Analysis

Many researchers have investigated ways to interpret GPR data of concrete structures, especially bridge decks. Although several

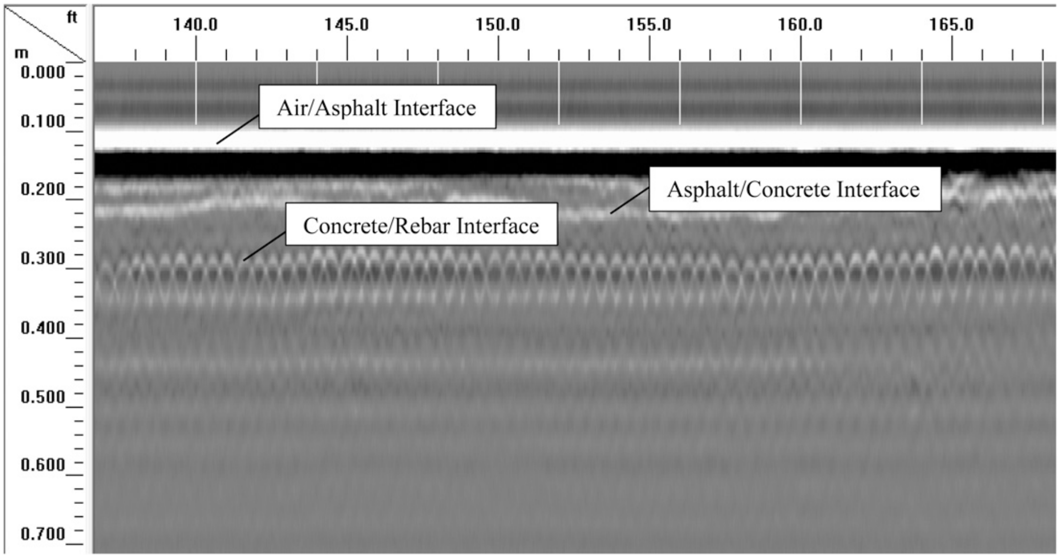

Fig. 1. Typical GPR image for concrete bridge decks with asphalt overlay

approaches have been proposed (Chung et al. 1992; Chung et al. 1993; Barnes and Trottier 2004; Tarussov et al. 2013; Dinh et al. 2013), the one based on reflection amplitude is still the most commonly used technique. The standard test method issued by ASTM is also a method based on amplitude analysis.

The basic assumption behind amplitude analysis is that GPR is considered simply as a measuring device. Therefore, it analyzes GPR data based on the reflection amplitudes measured at various interfaces, i.e., asphalt-concrete, top rebar, bottom rebar, and slab bottom. By normalizing reflection amplitudes and contour mapping, the analyst will infer the condition of the deck in question according to the attenuation of GPR signals. A detailed description of the method can be found in Maser and Bernhardt (2000), Parrillo et al. (2006), and ASTM D6087-08 (ASTM 2008).

According to Parrillo et al. (2006), however, the amount of deterioration should not be determined based solely on colors on the contour map. They pointed out that even a new deck will contain some range in rebar reflection amplitudes due to rebar depth variation. For the same reason, Geophysical Survey Systems (GSSI) recommends that the amplitude interpretation technique is not appropriate for a deck with no deterioration or a deck with near-total deterioration (GSSI 2012). Even for a bridge deck with average deterioration, in addition to rebar depth variation, there are still several factors that may lead to the inefficiency of analyzing reflection amplitudes (Tarussov et al. 2013). These factors include reinforcing bar spacing, surface properties, structural variation, construction quality, and so on. Up to the time of the current research, rebar depth variation is the only factor that has been taken into account for condition map adjustment (Barnes et al. 2008). A brief description of the adjustment method is provided subsequently.

It is clear from the physical and theoretical points of view that the reflection amplitude at each rebar depends on the distance (depth) from the concrete surface to the rebar itself, if bare concrete decks are concerned. There are two physical principles governing this amplitude reduction, namely, (1) the inverse-square law and (2) attenuation in the traveling medium. Possibly, because the amplitude variation due to the inverse-square law is small, only attenuation in the traveling medium was taken into account by Barnes et al. (2008). Specifically, when normalized reflection amplitudes for a concrete deck were plotted versus two-way travel time, a general decreasing linear trend was observed. Based on this observation, for depth correction, they proposed that, first, a quantile linear regression fitting be 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 the amplitude map would be the same as the conventional amplitude method.

As stated in the research objectives, the amplitude method is investigated for its capability in analyzing time-series data of concrete bridge decks. This investigation is performed for a bare concrete bridge deck in New Jersey with two data sets, collected in 2008 and 2013, respectively. The bridge was built in 1978, and, with 5-year separation, it is expected that the deck condition has undergone some changes and these changes should be somehow observed. Two data sets were collected at the same surveying lines using the same GSSI equipment type, i.e., a ground-couple radar system with a 1.5-GHz center frequency. Because the data set in 2008 covers only half of the deck width, the time-series analysis can only be implemented for this limited area. Each data set contains eight scan lines with 0.6096-m (2-ft) spacing, and the first line was 0.3048 m (1 ft) offset from the curb. The data were analyzed using both amplitude methods, i.e., without and with depth correction using the method described previously. The results are shown in Figs. 2 and 3, respectively.

As can be seen from Figs. 2 and 3, the results from the amplitude analysis either without or with depth correction clearly suggest the improvement of the deck condition over time. The attenuation maps in 2013 seem to come from a better concrete deck in comparison with the ones in 2008. This result was not expected and cannot be accepted because there has been no intervention performed on the bridge between 2008 and 2013.

Methodology and Model Development

Having studied the problem associated with the aforementioned amplitude method, the ideal way to find a condition change associated with any concrete bridge deck deterioration is by comparing current GPR signals with themselves, i.e., at the same location but taken previously or, ideally, when the bridge is newly constructed. In other words, instead of interpreting based on the relative difference between amplitudes from only one scan, a more appropriate way should be analyzing based on the difference between

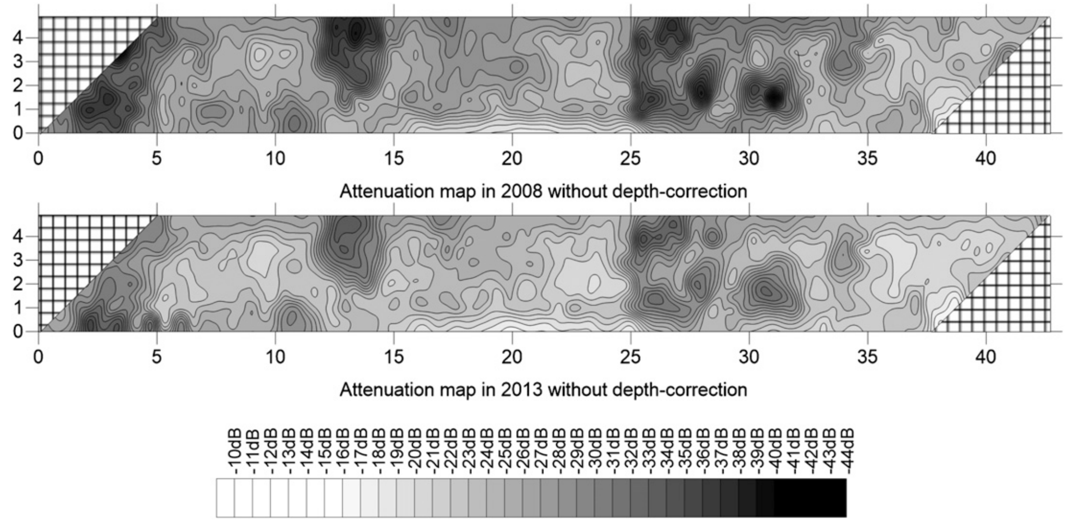

Fig. 2. Attenuation maps of two data sets without depth correction

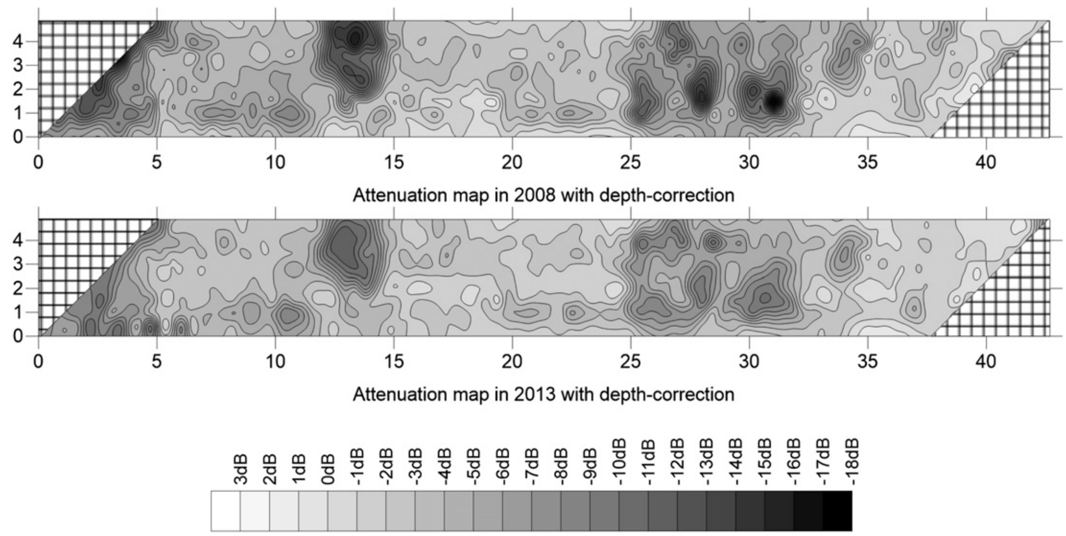

Fig. 3. Attenuation maps of two data sets with depth correction

time-series data. The overall workflow proposed for the long-term monitoring condition of concrete bridge decks using GPR is presented in Fig. 4. As can be seen, when a bridge deck is still in good condition, baseline GPR data and scan locations, i.e., scanning paths, should be recorded and stored in the database. Periodically, each time during the operational and maintenance stage or whenever the deck needs to be inspected, new GPR data at the same scan lines using the same equipment type will be collected. Then, the comparison for each pair of GPR individual signals (A-scans) collected at the same location will be performed using the model developed in this study. Finally, based on the comparison result, the condition at the inspected location will be predicted. Theoretically, it is clear that the more similarity between the two signals (new versus baseline), the less change in the concrete condition at the inspected location. Doing the analysis this way eliminates the need to look for sound concrete areas on the bridge to obtain the reference signals if the visual analysis method is concerned. Not only that, by using original signals, abnormal signals due to structural variation can also easily be observed and differentiated with corrosion-induced defects.

In the signal processing research domain, cross-correlation is the technique for measuring the similarity between two signals as a function of a time-lag applied to one of them. Correlation-based methods have been used extensively for many applications, such as object recognition, motion analysis, industrial inspection, and so on. For example, Tsai et al. (2003) studied the use of cross-correlation for defect detection in complicated images of industrial inspection. Giachetti (2000) proposed using pattern (template) matching to compute image motion from a sequence of two or more images, in which the displacement between two images was calculated based on the correlation measure between them. In a very interesting study, Brunelli and Poggio (1993) compared two different techniques for human face recognition; the first technique was based on the computation of a set of geometrical features, whereas the second one was based on correlation-based template matching. The same database that included frontal images of 47 people was used for the two techniques. Amazingly, the result favored template matching, which obtained perfect recognition, whereas the method based on geometrical features obtained only 90% correct recognition.

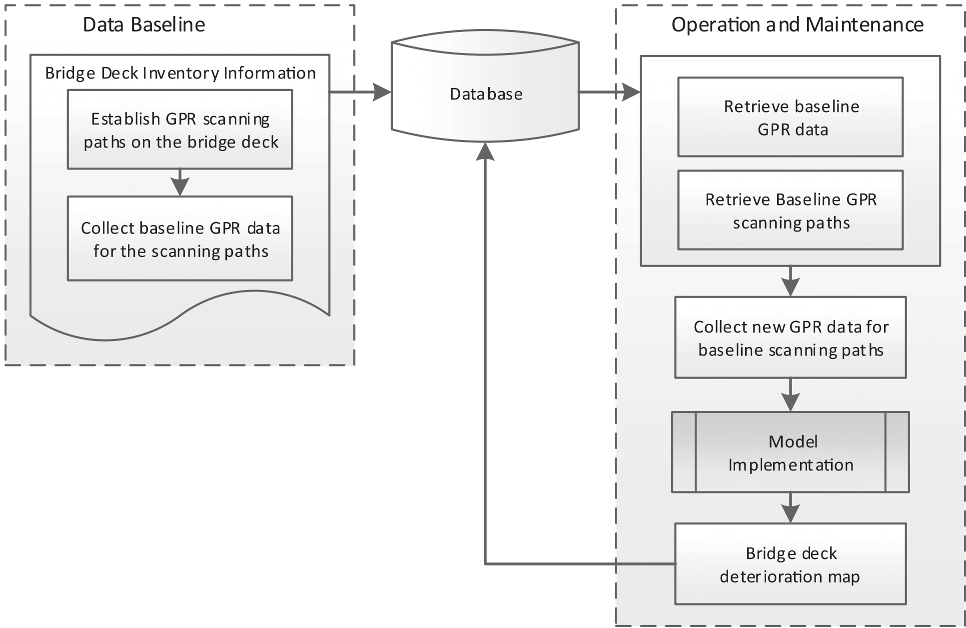

Fig. 4. Long-term condition assessment workflow of concrete bridge decks using GPR

Regarding the computation algorithm, Eq. (1) can be used to compare the similarity between two signals simply, without time difference. In the equation, ρ_{xy} is the normalized correlation coefficient between two digitized signals x_t and y_t. Actually, it is simply the normalized covariance between variables x_t and y_t. As can be seen, the value of ρ_{xy} lies between -1 and 1, and the closer to unity, the more similar the two signals

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

where $\gamma_{xy} = E[(x_t - \mu_x)(y_t - \mu_y)]$ is the covariance between x_t and y_t; μ_x and μ_y = means of x_t and y_t, respectively; and σ_x and σ_y = SDs of x_t and y_t, respectively.

Fig. 5 illustrates the idea for comparing the similarity between two GPR signals, in which the two waveforms needing to be compared are plotted in the same graph. The signals were collected using a GSSI 1.5-GHz antenna. Each waveform is sampled, and the voltage amplitudes in the data unit are measured at 512 points along each scan (GPR trace or A-scan). However, the first 10 samples are removed from each waveform because this section contains a lot of noise. Using Eq. (1), the correlation coefficient obtained for the two signals is 0.9008.

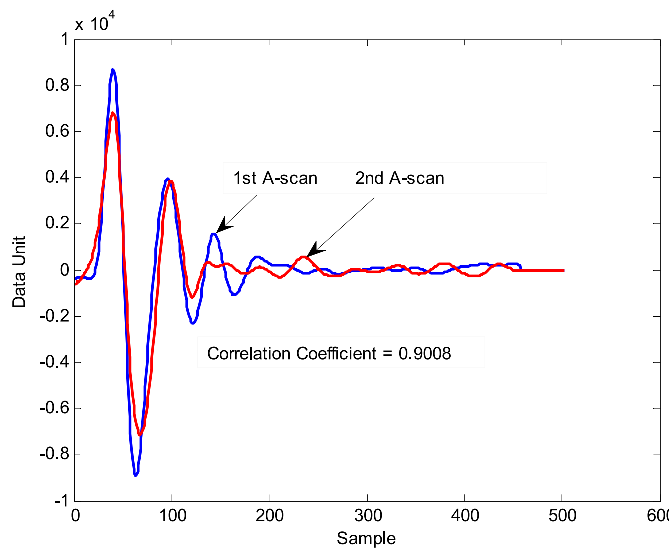

Fig. 5. Correlation between two GPR signals

It should be noted that interpreting GPR data based on signal similarity is much more comprehensive than simply comparing amplitude. Specifically, a correlation analysis takes into consideration two important pieces of information: the amplitude and the shape of an individual signal. For example, it is known from theory and experiment that when a delamination develops in the concrete and is big enough or filled with water, one more reflection from this layer would be observed in the scan (Scott et al. 2001). Whereas this reflection may affect top rebar reflection amplitude, it would be more sensitive to the correlation coefficient because of change in the shape of the signal. Much more than that, whereas the amplitude method mainly employs the signal at the center of the top rebar and then interpolates the condition for other positions between bars along the same scan path and between individual scan paths themselves, the previously mentioned correlation-based method can predict condition changes at any location on the profile. The reason is that, if that location does not have reflection from the top rebar, it still has reflection from the bottom rebar or from the slab bottom. So, if delamination develops or if chloride ingression causes amplitude attenuation at one of these layers, then they would affect the correlation coefficient.

One more important thing that also should be noted regards gain setting during the GPR scan; this factor actually does not cause any problems for correlation-based interpretation. The reason is that, if a constant (single-point) gain is used during scanning, it may amplify or diminish the amplitude but will not make any change to the overall shape of the signal. Therefore, it has no impact on the correlation coefficient. Even if one used a complicated gain setting when collecting the data, GSSI *RADAN 7* software has a function to restore the data as if no time-variable gain was applied to each of the unique, digitized samples along every individual GPR trace (A-scan).

After computing the correlation coefficient for each location, a contour map of correlation coefficients will be created. This contour map will delineate areas with different rates of signal changes. In principle, a lower correlation coefficient indicates a more deteriorated location. However, because some signal variation may be caused by error in line positioning, system instability, EM noise in the environment, or changes in weather and moisture condition instead of concrete deterioration, calibrating a threshold of correlation coefficients for the statistically significant confirmation of concrete deterioration is desired. The purpose of such a threshold is to avoid false-positive diagnosis, i.e., diagnosing deterioration where in fact there is none, and its calibration will be the subject of a future study.

For clarification, it is necessary to point out the difference between the proposed methodology and the time-series analysis commonly understood by the research community. Whereas the current research based on comparing GPR waveforms collected for the same deck location is used to monitor deterioration progression over time, the purpose of the conventional time-series analysis is either (1) to model the stochastic mechanism that drives an observed series or (2) to forecast the future values of a series based on its historical data (Cryer and Chan 2008). In the literature, the time-series analysis method has been applied by Attoh-Okine (1994) to model pavement thickness profiles obtained from GPR data. However, instead of true time series, distance scale data were used in that study.

Case Study Implementation

To validate and illustrate the implementation of the proposed methodology, again the RC bridge deck in New Jersey is studied. Because the ideal data set from when the deck was new is not available, the one from 2008 is used as the baseline. So, the question that the model developed in this study will be able to answer is how much change has happened on the deck and which regions tended to deteriorate more or less during the 2008–2013 time period. It is noted that, although the two data sets in 2008 and 2013 were collected at the same surveying lines using the same equipment as described previously, some differences in the scan setting did introduce discrepancies in the initial data sets before processing. However, with the capability of *RADAN 7* software to apply similar postprocessing parameters to these data sets, the differences have been minimized. Detailed problem and data processing are described in the following paragraphs.

As explained previously, the first and maybe the most difficult step in implementing the proposed methodology is to make sure that two profiles of the two data sets for the same scan line begin and end at the same location. In addition, to compare A-scans, the two profiles should have the same number of scans per unit length. These requirements are not readily met from the data collection, as illustrated in Fig. 6. As can be seen in Figs. 6(a and b), two profiles were collected using a different number of scans per unit length and they did not start at the same location or at the deck joint. However, using available functions in the *RADAN 7* software, such as *distance normalization* to adjust varying data to a constant number of scans per unit length and *edit block* to cut profiles so that unwanted data from approach ramps and expansion joints at abutments are not included as the RC deck, the two profiles can be processed to match exactly the location and number of scans, as shown in Figs. 6(c and d). It is noted that some condition changes between 2008 and 2013 can be visually observed from these two processed profiles.

In the second step, the processed *RADAN 7* files are converted to ASCII format. These ASCII files are then read by a *MATLAB 2013a* program developed by the first author to compute the correlation coefficient and assign a coordinate for each A-scan location. The output of the *MATLAB* program is also an ASCII file that contains information on the coordinates of each A-scan couple and their corresponding correlation coefficients. This file is then read by *Surfer 10*, a graphing and mapping software, and a contour map is produced. The final output of the proposed model is a correlation coefficient map presented in Fig. 7.

It is noted that the map in Fig. 7 shows only relative deterioration between two consecutive scans (i.e., between 2008 and 2013). What is shown in the figure is that the deck has undergone certain deterioration, but the deterioration rates are not the same for all of the locations—some areas have deteriorated faster than others.

Discussion

This case study clearly shows the simplicity of the proposed methodology. In comparison with other available data-analysis methods, it can be implemented in a shorter period of time and can be automated by computer software. Specifically, using the correlation method, the analyst does not need to pick the amplitude for each individual rebar, which is a time-consuming and tedious process. Instead, the analyst only

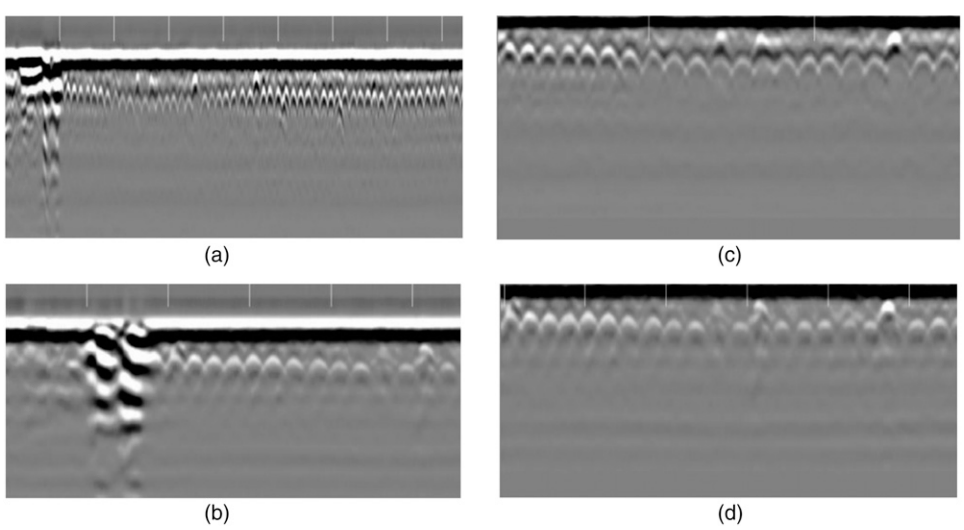

Fig. 6. (a) Unprocessed profile, 2008; (b) unprocessed profile, 2013; (c) processed profile, 2008; (d) processed profile, 2013

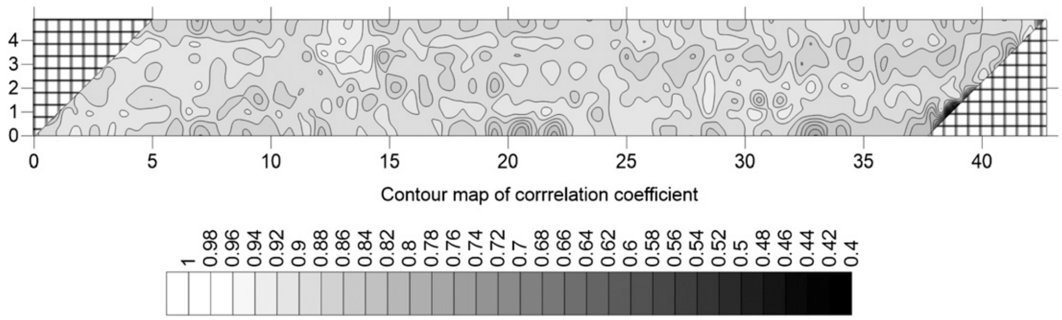

Fig. 7. Relative deterioration map between two consecutive scans

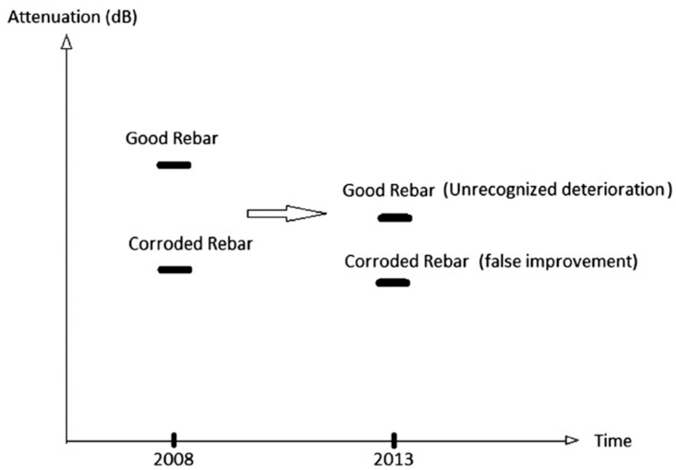

Fig. 8. Explanation for apparent deck improvement with amplitude interpretation

needs to normalize the distance and cut profiles, as described in the case study, to make sure that the profiles of the two scans start and end at the same points and have the same number of scans. Furthermore, unlike the amplitude method, correlation analysis can naturally eliminate all amplitude anomalies due to rebar depth and rebar spacing variation or those arising from structural and reinforcement layout. It can filter the defects associated with the deterioration process, such as corrosion and delamination, without generating errors caused by real construction variations either designed or built into the deck. These same variations are what typically require expert analysts to interactively interpret and/or review for quality assurance (QA) manually picked and processed rebar amplitude data. They are also the same structural features whose sudden and often unpredictable table signal features in GPR B-scan data cause automated rebar-picking programs to fail.

However, for the method to be added to current practice, a standard data-collection procedure should be followed. First, all of the data collection should use the same setting and equipment type, i.e., the same manufacturer, model, and frequency. Some important settings of the system for the application of this method include gain, range, filter, number of samples per scan, and number of scans per unit length. If one of these parameters was not set the same for the time-series data, then additional manipulation would be required to adjust the variance, and each data manipulation contributes to creating false differences between data that would not otherwise exist. A simple example was shown in the case study when distance normalization was used because of a difference in the number of scans per unit length between two data sets. This function is employed in *RADAN 7* software to adjust varying data to a constant number of scans per unit length. It reduces or adds A-scans based on an interpolation algorithm between adjacent waveforms. Ideally, adjustments like this should be minor, so setting the same number of scans per unit distance on each GPR data collection effort would be preferable to attaining equivalency via an interpolative method. Second, regarding scanning path positioning, these lines should be carefully set up the first time and recorded and stored in the database to facilitate the retrieval of their locations in the future. In this study, simple information recorded from previous data collection was used to locate previous scan lines. However, with the rapid advancement of modern technologies, such as real-time kinematic and differential global-positioning systems and the expected use of robotic data collection in the future (La et al. 2013), it is anticipated that positioning errors between time-series data would be minimized.

Possessing the property of both amplitude and visual analysis, the basic idea behind the correlation approach is very easy to understand. It predicts concrete deterioration based on any amplitude or shape change of the overall signal. The only drawback of the method is that it requires baseline data for implementation. Obviously, this will result in more initial inspection costs associated with the first data collection. However, this cost is small for GPR because the time it takes to scan an average deck is only several hours with one or two technicians. Even if the costs of traffic control are taken into account for a bridge with high traffic volume, in comparison with the time it will take to inspect the bridge in the future using a time-consuming and expensive method such as half-cell potential, a few hours of baseline GPR data collection would still be a cost-saving option.

Separate from its use for future time-series condition assessment, other justifications exist for collecting baseline data. First, the data can be used for inspection of construction quality, i.e., voids, cracks, or other anomalies due to poor construction. In some state DOTs, GPR use (1.5-GHz resolution or higher) is specified for QA verification of concrete cover regarding its compliance with construction specifications (Perkins et al. 2000). Furthermore, accurate knowledge about cover depth variation on new decks provides a basis for service-life modeling based on chloride diffusion (Weyers 1998; Liu and Weyers 1998; Suwito and Xi 2003; Li 2003), although most models erroneously assume that design cover or cover based on random sampling is representative of rebar depth throughout the deck. Hence, multipurpose use of the same initial baseline GPR data is justified and makes economic sense from many perspectives.

Another research question concerning the suggested frequency of GPR inspection for a bridge deck was also raised during this study. However, due to data limitations in this research, no conclusion can be drawn for this issue. It is suggested that, in the future, several pilot bridge decks should be monitored over the long term using the technique proposed in this study. Then, the deterioration information from these pilot projects can be used to determine the optimal GPR inspection frequency, based on the result of a life-cycle cost analysis.

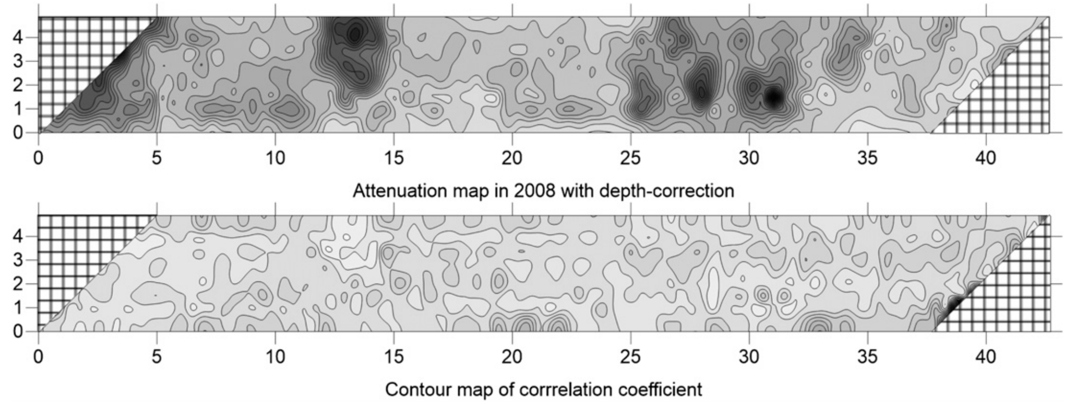

Fig. 9. Previous maps reorganized for comparison

Again, with the correlation coefficient map in Fig. 7, the problem with amplitude analysis described in the New Jersey bridge deck can now be explained. First, if the attenuation maps in Figs. 2 and 3 are analyzed in detail, a clear phenomenon can be seen in which the range of amplitude variation reduces between 2008 and 2013. Because no intervention action has been taken on the deck during this period, the only possible explanation for this phenomenon is that, during the 2008–2013 period, the sound concrete area in the 2008 map tended to deteriorate faster than the previously deteriorated region. This explanation can be visualized in Fig. 8, and its validation can be performed by comparing the correlation coefficient map with the depth-corrected attenuation map in 2008. For ease of comparison, these two maps are reorganized and shown again in Fig. 9. As expected, the regions that have a lower correlation coefficient tend to lie in those areas in good condition in the 2008 map.

Conclusions

Transportation agencies need accurate inspection techniques for assessing the condition of their bridges, especially concrete bridge decks. Presently, GPR is still being considered simply as a technique for detection of potential damage. The reason is that, based on the amplitude method, GPR provides condition maps with unpredictable accuracy. This unpredictability has been illustrated and the reason behind it has been clearly explained in this paper by using time-series data for a bridge deck in New Jersey. With the model using the correlation analysis proposed in this study, it is expected that GPR will be realized as an excellent NDE tool and practiced in the near future, not only for the detection of potential damage but also for reliably assessing the condition of concrete bridge decks. The only drawback to the method is that it requires baseline data to be collected when bridge decks are still in good condition. However, it is believed that the long-term benefits will outweigh the up-front cost of the first data collection. In the future, the method will be further developed when more time-series data are available.

Acknowledgments

The authors of this paper thank the Ministry of Transportation of Québec and Mitacs for their funding and support of this study. Also, they wish to thank Mr. John Tate, Warren County Department of Public Safety, who authorized their entry to the field for data collection.

References

ASTM. (2008). "Standard test method for evaluating asphalt-covered concrete bridge decks using ground penetrating radar." *D6087-08*, West Conshohocken, PA.

Attoh-Okine, B. N. (1994). "Time series analysis for ground penetrating radar (GPR) asphalt thickness profile." *Appl. Stochastic Models Data Anal.*, 10(3), 153–167.

Barnes, C. L., and Trottier, J.-F. (2004). "Effectiveness of ground penetrating radar in predicting deck repair quantities." *J. Infrastruct. Syst.*, 10.1061/(ASCE)1076-0342(2004)10:2(69), 69–76.

Barnes, C. L., Trottier, J.-F., and Forgeron, D. (2008). "Improved concrete bridge deck evaluation using GPR by accounting for signal depth–amplitude effects." *NDT & E Int.*, 41(6), 427–433.

Brunelli, R., and Poggio, T. (1993). "Face recognition: Features versus templates." *IEEE Trans. Pattern Anal. Mach. Intell.*, 15(10), 1042–1052.

Chung, T., Carter, C. R., Masliwec, T., and Manning, D. G. (1992). "Impulse radar evaluation of asphalt-covered bridge decks." *IEEE Trans. Aerosp. Electron. Syst.*, 28(1), 125–137.

Chung, T., Carter, C. R., Reel, R., Tharmabala, T., and Wood, D. (1993). "Impulse radar signatures of selected bridge deck structures." *Proc., Canadian Conf. on Electrical and Computer Engineering*, Vol. 1, IEEE, New York, 59–62.

Cryer, J. D., and Chan, K. S. (2008). *Time series analysis: With applications in R*, Springer, New York.

Dinh, K., Zayed, T., and Tarussov, A. (2013). "GPR image analysis for corrosion mapping in concrete slabs." *Proc., CSCE Annual Conf.*, Canadian Society for Civil Engineering, Montréal.

Geophysical Survey Systems (GSSI). (2012). *RADAN 7 manual*, Salem, NH.

Giachetti, A. (2000). "Matching techniques to compute image motion." *Image Vision Comput.*, 18(3), 247–260.

La, H. M., et al. (2013). "Autonomous robotic system for high-efficiency non-destructive bridge deck inspection and evaluation." *Proc., IEEE Int. Conf. on Automation Science and Engineering (CASE)*, IEEE, New York, 1053–1058.

Li, C. Q. (2003). "Life cycle modeling of corrosion affected concrete structures—Initiation." *J. Mater. Civ. Eng.*, 10.1061/(ASCE)0899-1561(2003)15:6(594), 594–601.

Liu, Y., and Weyers, R. E. (1998). "Modeling the time-to-corrosion cracking in chloride contaminated reinforced concrete structures." *ACI Mater. J.*, 95(6), 675–680.

Maser, K., and Bernhardt, M. (2000). "Statewide bridge deck survey using ground penetrating radar." *Proc., Structural Materials Technology IV: An NDT Conf.*, S. Alampalli, ed., Technomic, Lancaster, PA, 31–37.

MATLAB 2013a [Computer software]. Natick, MA, MathWorks.

Parrillo, R., Roberts, R., and Haggan, A. (2006). "Bridge deck condition assessment using ground penetrating radar." *Proc., European Conf. on Non-Destructive Testing (ECNDT)*, European Federation for Non-Destructive Testing, Brussels, Belgium, 25–29.

Perkins, A. D., Amrol, J. J., Romero, F. A., and Roberts, R. L. (2000). "DOT specification development based on evaluation of ground-penetrating radar system performance in measuring concrete cover (reinforcement depth) on new bridge deck construction." *Proc., Structural Materials Technology IV: An NDT Conf.*, S. Alampalli, ed., Technomic, Lancaster, PA, 53–60.

RADAN 7 [Computer software]. Salem, NH, Geophysical Survey Systems (GSSI).

Scott, M., Rezaizadeh, A., and Moore, M. (2001). "Phenomenology study of HERMES ground penetrating radar technology for detection and identification of common bridge deck features." *Rep. FHWA-RD-01-090*, Federal Highway Administration, U.S. DOT, Washington, DC.

Surfer 10 [Computer software]. Golden, CO, Golden Software.

Suwito, A., and Xi, Y. (2003). "Service life of reinforced concrete structures with corrosion damage due to chloride attack." Chapter 22, *Life-cycle performance of deteriorating structures*, D. M. Frangopol, E. Brühwiler, M. H. Faber, and B. Adey, eds., ASCE, Reston, VA, 207–218.

Tarussov, A., Vandry, M., and De La Haza, A. (2013). "Condition assessment of concrete structures using a new analysis method: Ground-penetrating radar computer-assisted visual interpretation." *Constr. Build. Mater.*, 38(Jan), 1246–1254.

Tsai, D. M., Lin, C. T., and Chen, J. F. (2003). "The evaluation of normalized cross correlations for defect detection." *Pattern Recognit. Lett.*, 24(15), 2525–2535.

Weyers, R. E. (1998). "Service life model for concrete structures in chloride laden environments." *ACI Mater. J.*, 95(4), 445–453.