NDT&E International 83 (2016) 48–58

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Understanding depth-amplitude effects in assessment of GPR data from concrete bridge decks

Kien Dinh [a,*], Nenad Gucunski [b], Jinyoung Kim [a], Trung H. Duong [a]

[a] Center for Advanced Infrastructure and Transportation, Rutgers University, USA
[b] Civil & Environmental Engineering, Rutgers University, USA

ARTICLE INFO

Article history:
Received 6 January 2016
Received in revised form
5 June 2016
Accepted 10 June 2016
Available online 11 June 2016

Keywords:
Ground penetrating radar (GPR)
Nondestructive evaluation (NDE)
Bridge deck
Concrete
Inspection
Condition assessment
Deterioration

ABSTRACT

The variation of concrete cover thickness on bridge decks has been observed to significantly affect the rebar reflection amplitude of the ground penetrating radar signal. Several depth correction approaches have been previously proposed in which it is assumed that, for any bridge, at least a portion of the deck area is sound concrete. The 90th percentile linear regression is a commonly used procedure to extract the depth-amplitude relationship of the assumed sound concrete. It is recommended herein that normalizing the depth-dependent amplitudes be divided into two components. The first component takes into account the geometric loss due to inverse-square effect and the dielectric loss caused by the dissipation of electromagnetic energy in sound concrete. The second component is the conductive loss as a result of increased free charges associated with concrete deterioration. Whereas the conventional depth correction techniques do not clearly differentiate the two components and tend to incorporate both in the regression line, they are separately addressed in this research. Specifically, while the first component was accounted for based on a library of GPR signals collected from sound areas of twenty four bare concrete bridge decks, the conductive loss caused by an increased conductivity is linearly normalized by the two-way travel time. The implementation of the proposed method in two case studies showed that, while the method significantly improves the accuracy of GPR data analysis, the conventional methods may lead to a loss of information regarding the background attenuation that would indicate the overall deterioration of bridge decks.

1. Introduction

Ground penetrating radar (GPR) has been commonly used as a rapid, non-invasive technology for evaluating effects of corrosion in concrete bridge decks [1–8]. During a GPR scan, the GPR antenna sends a short pulse of electromagnetic (EM) energy into the bridge deck. When this EM wave energy encounters interfaces between different materials or substances in the deck, such as air/asphalt, asphalt/concrete, concrete/rebar, or slab bottom/air, a part of the EM energy is reflected back and recorded. By numerically analyzing or visually reviewing the received signals, the corrosion affected bridge deck sections can be identified and differentiated from sound sections. The premise is that the corrosive environment with its main contributors, such as moisture, chlorides, rust and cracks, will absorb more EM energy and more highly attenuate the signals.

As a nearly perfect reflector of radio-frequency EM energy, steel rebars are the most commonly used reflection interfaces for assessing the attenuation of GPR signals in concrete bridge decks [1]. Specifically, to assess the condition of a bridge deck using this evaluation technique, reflection amplitudes at the top rebar layer are picked from the GPR data and contour mapped based on their corresponding coordinates. Using certain thresholds, areas with high signal attenuation in the obtained map would be described as a deteriorated concrete. However, since it is observed that the reflection amplitude at a particular rebar largely depends on the concrete cover thickness at that rebar location, there is a clear evidence that the depth-dependent amplitudes need to be normalized before they can be assessed [3,6].

The current practice is to extract the depth correction function from the GPR data for each particular bridge deck. A major assumption of this approach is that, for any bridge deck, at least ten percent of the deck area is sound concrete. In addition, since it was observed that in most cases the top upper points of the scatter plot (logarithmic amplitude versus two-way travel time), points

* Corresponding author.
E-mail addresses: kien.dinh@rutgers.edu (K. Dinh), gucunski@rci.rutgers.edu (N. Gucunski), rutgers.no1@rutgers.edu (J. Kim), trung.duong@rutgers.edu (T.H. Duong).

http://dx.doi.org/10.1016/j.ndteint.2016.06.004
0963-8695/

associated with concrete in a more sound condition, tend to form a straight line, a 90th percentile linear regression was proposed as a standard depth-amplitude relationship for depth correction [3]. A GPR expert would frequently approximate this relationship by drawing a line manually in the scatter plot [6].

It is realized that the current practices have limited the full potential of GPR in the inspection of bridge decks. Specifically, Geophysical Survey Systems (GSSI) [9] stated that a GPR amplitude interpretation is not appropriate for a bridge deck with no deterioration or a highly-deteriorated bridge deck. In addition, GSSI suggested that, as the technique shows only a relative change across a single deck, data from different bridge decks cannot be compared. As a consequence, GPR might not use its potential to the fullest extent as a tool for condition assessment of bridge decks on the network level, where the conditions of different decks need to be reliably assessed and objectively compared for project prioritization.

The ultimate goal of this study was to enhance the accuracy of GPR data analysis so that the application of GPR can be expanded for bridge decks in a full range of conditions, i.e., from a healthy to a totally deteriorated bridge deck. It is anticipated that this goal can be obtained by better understanding and accounting for the depth-amplitude effects through investigation of GPR data for a large number of bridge decks. The availability of the results from other nondestructive evaluation (NDE) techniques will be used to identify GPR signals collected on sound bridge deck areas. Specifically, three research objectives were identified:

i. To develop understanding of the impact of rebar depth on GPR signal loss;
ii. To examine a method for objective comparison of GPR data from different bridge decks; and
iii. To normalize the depth-amplitude effects for consistent evaluation of bridge decks.

The data used in this study were primarily collected within the Federal Highway Administration's (FHWA's) Long-Term Bridge Performance (LTBP) Program. As a part of the program, representative samples of bridges throughout the US are inspected, evaluated and monitored over a period of time. Within the scope of the program, a cluster of twenty-four bridge decks in the Mid-Atlantic region was surveyed in 2013 by the team from the Center for Advanced Infrastructure and Transportation (CAIT) at Rutgers University, using a range of NDE techniques. All the decks were selected by the research team in coordination with the FHWA, industry partners and participating State Departments of Transportation (DOTs) to be representative samples of bridges of the same type. As the first cluster, untreated/bare cast-in-place concrete decks that rest either on steel or prestressed concrete girders were investigated. Five NDE technologies were deployed on each surveyed bridge deck. GPR was used to characterize the corrosive environment and provide the overall condition assessment; half-cell potential (HCP) to find areas with probable active corrosion; electrical resistivity (ER) to describe the corrosive environment and estimate corrosion rates; impact echo (IE) to detect and characterize concrete delamination, and ultrasonic surface waves (USW) to assess concrete quality through measurement of concrete elastic modulus.

A ground-coupled 1.5-GHz GPR antenna was employed on all bridge decks. Since all surveyed bridge decks had the top rebar in the transverse direction, the GPR scanning direction was always parallel to the traffic. With respect to the survey setup, whereas for other technologies the data were collected on a 0.6 m × 0.6 m (2-ft × 2-ft) grid, the distance between adjacent GPR survey lines was 0.6 m (2-ft). The first line of the survey grid was 0.3 m (1-ft) offset from the parapet or a curb. Whereas the data from the LTBP Program cluster bridges were used to develop the insight into the depth-amplitude relationship, data from other bridge decks were utilized as a validation of the study results. As such, it is important to note that the data for these decks were collected using the same equipment and protocols as for the cluster bridges' decks.

2. Attenuation of EM waves in concrete decks

The reduction of EM wave amplitude varies with the medium the wave propagates in. In the simplest case, as an EM wave travels in the vacuum, the reduction of the amplitude at any point in the space is approximated by the inverse-square law. This means that the intensity of the electromagnetic field oscillation at a point will be proportional to the inverse of the square of its distance to the EM wave source. This phenomenon of amplitude reduction (*geometric loss*), however, should be differentiated from the attenuation, i.e., energy loss, when the EM wave travels in another substance.

In a pure dielectric material (no free charges moving between atoms or molecules), the attenuation of the EM wave amplitude is called the *dielectric loss*. Physically, it is caused by the damping forces in each atom that resist the motion in atomic oscillators [10]. Because of these resistance forces, a part of the EM wave energy will be dissipated as heat. Mathematically, the rate of this energy loss is specified by the imaginary part of the *refractive index (n),* whereas the real part of such index will determine the speed of the EM wave propagation. The equation of the EM wave travelling in a dielectric material is provided in Eq. (1) [10].

$$E(z) = E_0 e^{-\omega n_I z/c} e^{i\omega\left(t-\frac{n_R z}{c}\right)} \quad (1)$$

where:

$E(z)$ is the strength of the electric field at a distance z from the EM wave source.

E_0 is the strength of the electric field at the EM wave source.

ω is the frequency of the EM wave.

n_I is the imaginary part of the refractive index (n).

n_R is the real part of the refractive index (n).

As can be seen in the equation, the amplitude of EM wave in a dielectric decreases exponentially with the travelling distance. In addition, the attenuation will increase with the increase of the EM wave frequency. That explains why a lower frequency EM wave can penetrate deeper into the dielectric material than a higher frequency wave.

For newly constructed bridge decks, concrete is usually a dielectric and only dielectric loss will occur when GPR signals travel in such concrete, along with the beam scattering effect. However, when decks deteriorate, the electrical conductivity in concrete will increase due to the presence of chlorides, moisture, salts and rust. In other words, more free charges will be present in a deteriorated deck. As a consequence, when GPR signals travel, eddy currents will be induced in the concrete due to the presence of those free charges and the EM energy will also be additionally dissipated as heat. This attenuation mechanism is called the *conductive loss*. As can be realized, the conductive loss will be proportional to: (1) the density of free charges in concrete, (2) how easily the charges can move (dry or wet concrete), and (3) the distance that a GPR signal travels in such a conductive path.

3. Research methodology

As the conductive loss due to concrete deterioration is of main interest in using the GPR for bridge decks, it is clear that for the purpose of deck condition assessment this component be separated from the amplitude reduction caused by the beam scattering effect and the dielectric loss. To do so, the amplitude reduction due to the beam scattering effect and the dielectric loss must be well understood and be subtracted from the total amplitude loss. Eq. (2) below provides a representation of how the depth-amplitude effects should be accounted for when assessing GPR data from concrete bridge deck surveys.

$$A_{Total}(d) = A_{geometric\ loss}(d) + A_{dielectric\ loss}(d) + A_{conductive\ loss}(d) \tag{2}$$

where:

d is the concrete cover thickness (rebar depth).
A_{Total} is the total attenuation of amplitude.
$A_{geometric}$ is the attenuation due to geometric loss.
$A_{dielectric\ loss}$ is the attenuation due to dielectric loss.
$A_{conductive\ loss}$ is the attenuation due to conductive loss (concrete deterioration).

The total effect of the attenuations discussed above could be studied directly, if one could measure exactly the strength of the electric field at any point in concrete. However, that cannot be done by GPR, because the technique only measures the strength of reflection at various interfaces in a bridge deck. In other words, GPR is an indirect method to estimate the attenuation of EM waves of a certain frequency range in concrete. Compared to the hypothetical direct measurement of strength of electric field mentioned above, the accuracy of the GPR technology will be lower and it will be affected by a number of factors.

Let us consider a simple case of bare concrete deck, as being examined in this research. First, the top deck properties, such as the smoothness or dielectric contrast, would determine how much EM energy can penetrate into the concrete, and how much of it can be received at the antenna when the reflected signals come back. As can be imagined, because of the two-way travel path, the local variation of top deck properties will affect twice the amount of energy recorded in each A-scan. The second influential factor is the rebar configuration in a deck. Specifically, in addition to the effects of rebar depth variation that is addressed in this research, the rebar size (diameter), spacing and orientation, e.g., skewed bars, will also have some impact on the rebar reflection amplitudes recorded.

The studied problem is very complex. Additional factors can affect GPR measurements, such as concrete mixes, deck moisture and weather condition at the time of the GPR surveys, and so forth. Therefore, it is not intended in this research to study the effects of all factors influencing GPR reflection amplitudes. Instead, except for the rebar depth variable that will be modeled explicitly, all other variables will be considered as random factors. The reliability of the obtained model will then be evaluated based on the coefficient of determination (R^2). For instance, suppose that a coefficient of determination of 0.8 is found for the depth-amplitude model established from an entire large dataset. In that case, one might ask whether the model takes into account the rebar diameter of a particular bridge deck. Since the large dataset used to build such a model has already included different rebar sizes, concrete mixes, skewed angles, etc., without the knowledge of those parameters of a specific bridge deck and by a blind application of the depth-amplitude model, one can say that there is an 80% probability that what he/she has done is correct.

The above idea is the same as those employed in well-founded evaluation techniques. For example, the HCP method is also based on the stochastic concept, where it states that a potential measurement below −350 mV corresponds to a 90% probability of active corrosion [11]. The reason for this is that other variables may affect a HCP measurement, in addition to the rebar corrosion. Whereas these variables may be accounted for in the future when they are better understood, until then they should still be considered as random factors. Finally, it is clear that, if one variable accounts for one percent variation of a parameter of interest, and furthermore the variable is hard to be modeled, it should be neglected.

As can be realized from the above discussion, the combination of the geometric loss and the dielectric loss can be evaluated by selecting and analyzing GPR signals from sound concrete. This was feasible in the current research as the combination of HCP, ER, and IE results was available to help reliably identify sound concrete areas on the cluster bridges' decks. Specifically, the criteria used in defining sound concrete areas from these techniques were as follows: (1) potential measurements greater (more positive) than −200 mV for HCP [11]; (2) electrical resistivity greater than 100 kOhm cm for ER [12]; and (3) no signs of delamination for IE [13]. After the sound concrete areas have been identified, the GPR data from these areas were extracted to study the effect of beam scattering and the dielectric loss on the rebar reflection amplitude.

3.1. Amplitude extraction

Common practice, as well as according to ASTM D6087-08 [14], rebar reflection amplitudes are obtained from picked rebars in migrated GPR profiles (B-scans). While the migration technique was developed in geophysics to identify true location of subsurface objects, its application to bridge deck evaluation introduces additional uncertainties in the GPR amplitude analysis for two reasons. First, since the migration sums up all the reflection amplitudes on a hyperbola that represents reflections from a rebar, rebars at different depths are affected differently by this operation. As a deeper rebar will appear in more A-scans than a shallow rebar (due to beam spreading), application of migration will amplify more the deeper rebar. Second, since migrated profiles depend on the signal speed used for this transformation, amplitudes extracted from these profiles may vary considerably with the choice of optimal velocity.

For the above reasons, rebar reflection amplitudes in this study were picked directly from the original GPR profiles. The only manipulation made to each GPR profile prior to rebar picking was a time-zero correction. Whereas the purpose of this step was to ensure that a correct two-way travel time (TWTT) can be obtained for each rebar, it does not affect or transform the amplitudes. A total of 23,587 data points (rebar peaks) were obtained for sound concrete areas identified from the decks of cluster bridges. The rebar reflection amplitudes from different bridge decks need to be normalized before they can be compared.

3.2. Amplitude normalization

There are two reasons why the GPR results from different bridge decks should be compared with caution. First, the GPR data for different bridge decks may be collected using different GPR units, which may have different transmit powers or center frequencies. Second, even if the data are collected using the same GPR equipment, different gains may be set during the data collection. Whereas it is not appropriate to compare GPR data collected from antennas of different frequencies, it is assumed herein that the data from antennas of the same frequency, or from the same GPR unit, will compare reasonably well.

In the current practice, reflection amplitudes are usually normalized by the maximum measurable amplitude of the data acquisition system of the GPR unit, e.g., 32,768 data units for the 16 bit data [3]. However, this normalization method does not take into consideration the difference in the transmission power between antennas or gains set during the data collection. As a result, using the same GPR unit, if two different gains are employed for the same bridge deck, the amplitudes obtained will be different for

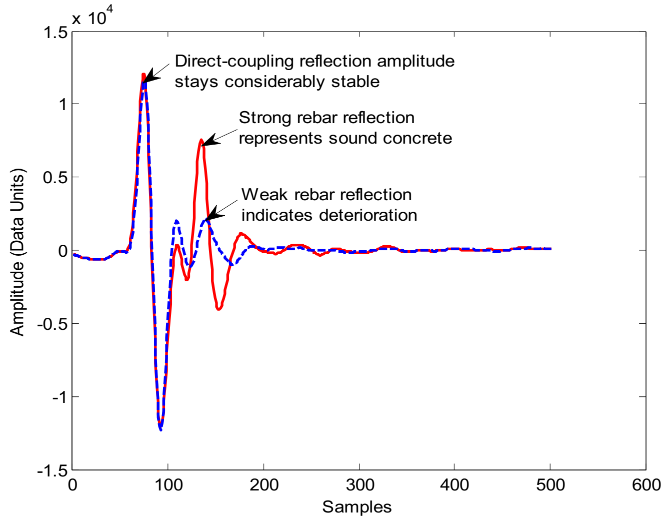

Fig. 1. Effects of deterioration on GPR signal amplitude.

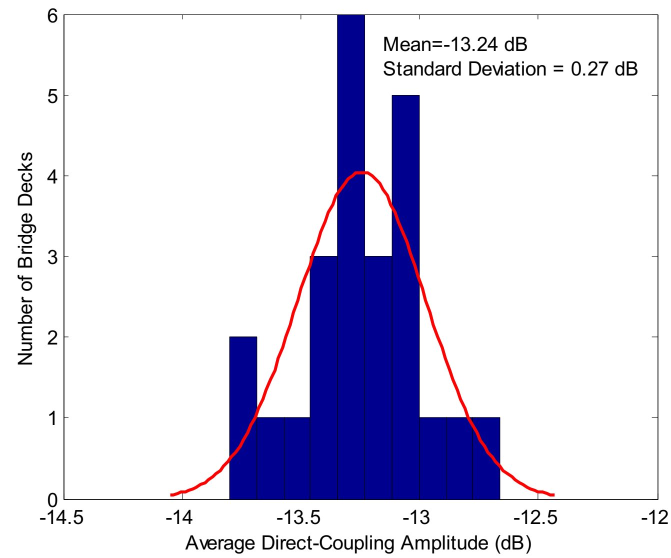

Fig. 2. Distribution of average direct-coupling amplitude for cluster bridge decks.

the two data sets. To ensure that the data are comparable between different bridge decks, another normalization method is needed.

Ideally, the normalization should be done by measuring the reflection amplitude using a metal plate at a specific distance before each survey. Such a data, unfortunately, does not usually exist when the GPR data collection is performed using ground-coupled antennas. As an alternative, the direct-coupling reflection can be used for such purpose. Specifically, direct-coupling is the effect in which the "air wave" and the "surface wave" merge when a GPR antenna is moved toward the surface of a bridge deck. Since having the air wave component that reflects the transmit power of the GPR unit and gain set during data collection, the direct-coupling reflection can serve as a benchmark for normalization. Theoretically, the amplitude variation may exist in the direct-coupling reflection from the surface wave component due to the local condition of concrete. However, as illustrated in Fig. 1, using the same equipment and setting, the direct-coupling amplitudes are almost identical between a waveform collected on a sound and a deteriorated deck. This observation forms the basis for using direct-coupling as the normalization criterion in this research.

Specifically, and as defined in Eq. (3), the normalization is done by dividing the amplitude (in data units) of each rebar reflection by the average direct-coupling amplitude measured for each corresponding bridge deck. The purpose of using the average amplitude is to minimize the effects of irregular direct-coupling reflections that may occur when GPR antenna passes over a pothole or a patch on bridge deck. As it can be imagined, the process will eliminate the difference in the transmit power of the antenna or gain set during the data collection, as long as the gain was set as a constant (one point gain). For the same GPR unit, if a constant gain of 1 dB is used, the direct-coupling reflection amplitude would be amplified by 1 dB, as would be the reflection amplitude from a rebar.

$$\text{Normalized Amplitude}(dB) = 20 * \log_{10}\frac{\text{Measured amplitude in data unit}}{\text{Average direct coupling amplitude}} \quad (3)$$

To support the validity of the direct-coupling normalization method, it is necessary to show a strong relationship between the transmit power of a GPR unit and the average direct-coupling amplitude collected on bridge decks. Decks of twenty-four cluster bridges were used for that purpose. Specifically, since a different gain was set for each bridge deck during the data collection, after the previously applied gain was removed from the GPR data, the average direct-coupling amplitude was computed for each deck. These amplitudes were then converted to decibels by normalizing them to the maximum measurable amplitude, i.e., 32,768 data units for the 16 bit data acquisition system used in this research. The distribution of average direct-coupling amplitudes obtained for twenty-four cluster bridges' decks is plotted in Fig. 2. As can be seen, the variation in average direct-coupling amplitude (standard deviation of 0.27 dB) is negligible, considering the commonly used threshold of -6 to -8 dB for identifying concrete deck deterioration [14]. Such variation might come as a result of differences in the overall condition of bridge decks, signal noise, moisture, weather condition, and so forth.

The TWTT and amplitude data obtained using the two normalization methods (conventional method versus direct-coupling normalization) for sound areas of the cluster bridge decks are provided in Fig. 3. As can be seen, compared to the conventional method, the variation of the amplitude reduces significantly using the direct-coupling normalization technique. Visually, the data points in Fig. 3b are more compact than those in Fig. 3a, meaning the amplitude from sound concrete can be predicted more accurately from its TWTT with the direct-coupling normalization method. Moreover, the linear trend of the scatter plots in Fig. 3 also suggests that, compared to the beam scattering effect, the dielectric loss is the dominant mechanism for amplitude loss in sound concrete. That linear trend can be predicted when the amplitudes in Eq. (1) are converted to decibels. The only difference here is the fact that the TWTT was employed instead of the true depth (z). Certainly, some uncertainty will be introduced by this convention in the modeling process. However, this convention was inevitable, because finding the true depth for each rebar is difficult, or time consuming.

In addition, it can be noticed, as pointed to in Fig. 3b, that there are a number of rebar peaks with reflection amplitudes stronger than the rest. Investigation of the data revealed that all these rebar peaks are from the same bridge deck. Interestingly, in that deck, all the abnormal amplitudes are from a single B-scan, right in the middle of the deck, whereas the amplitudes for the rest of B-scans show no abnormalities. Since the reason for the single scan deviation cannot be the change in rebar diameter, other unknown factors should have been responsible for such strong amplitudes. With respect to the entire data set examined, the percentage of those abnormal amplitudes is approximately 0.6%. Statistically, since this ratio is very small, the data points in Fig. 3b can be used

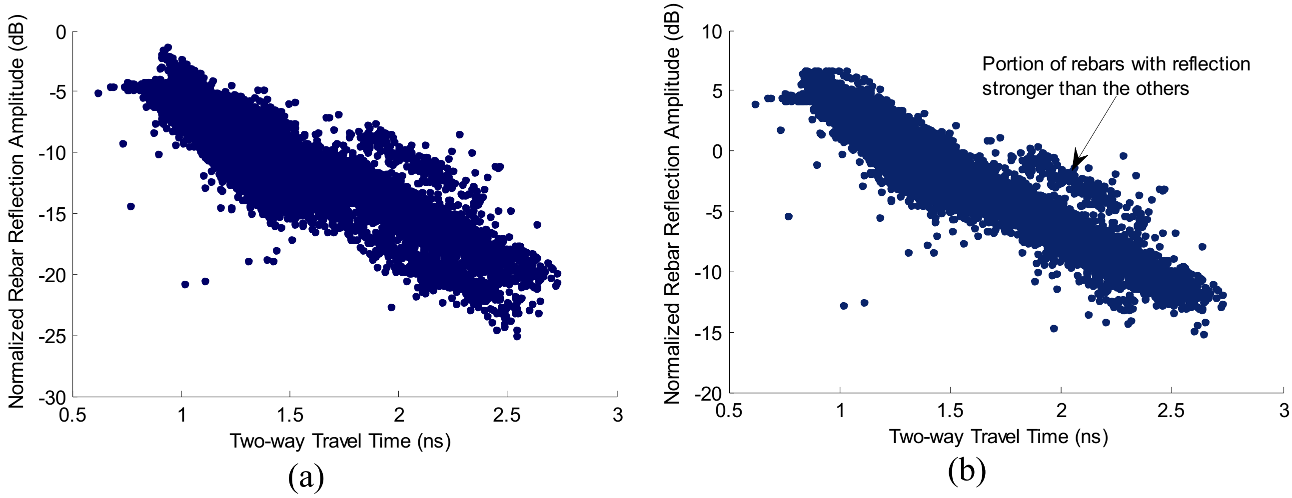

Fig. 3. Rebar reflection amplitude normalized by (a) maximum measurable amplitude and (b) average direct-coupling amplitude. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with confidence to extract the depth-amplitude relationship for depth correction of data for bare concrete bridge decks. For convenience, the area covered by these data points (blue dots) is called the "**healthy zone**" in this study.

3.3. Deterioration and depth-related amplitudes

In this section, GPR data from decks of varying condition from six bridges outside the LTBP cluster bridge study are investigated to better understand the effects of deterioration on depth-related amplitudes. Based on the results from other NDE techniques, including the HCP, ER and IE, the first deck was found to be fully sound, while the other decks manifested some signs of deterioration, i.e., active corrosion, higher anticipated corrosion rates, and/or delamination. The scatter plot of GPR data for each deck, after being normalized by the direct-coupling reflection, is superimposed on the healthy zone obtained in the previous step in Fig. 4. In addition, a 90th percentile linear regression was implemented for each data set, and also shown in Fig. 4, to study the rationale of the current depth correction practice. The results presented in Fig. 4 are discussed in the subsequent paragraphs.

It is clear that the data points for the first bridge deck (Fig. 4a) lie completely within the healthy zone, indicating that the bridge deck is in a good condition. The 90th percentile linear regression line matches the data field reasonably well, although looking a little bit more conservative. For the deteriorated bridge decks (Fig. 4b–f), it can be observed that portions of the data points fall outside the healthy zone. The area percentage of those data portions can be viewed as indicators of the scope (area percentage) of deck deterioration. For the last bridge deck in Fig. 4f, most of its data points lie outside the heathy zone. A small portion of the data within the healthy zone is however in its lower part.

The most interesting observation in Fig. 4 is, however, the slope of each regression line. As can be seen, the slopes of all regression lines appear greater than the slope of the healthy zone that is computed to be equal to 9.50. The differences are even bigger, if a mean regression is used for each data set, instead of the 90th percentile. These higher slopes can be attributed to the increase of concrete conductivity due to intrusion of moisture and chlorides, and deterioration. Those indicate that, even after the beam scattering effect and dielectric loss have been taken into account, it still appears that deeper rebars tend to attenuate more than shallower rebars. That means that the conductive loss will also be proportional to the distance a GPR signal travels. Clearly, if this attenuation component is not corrected for the rebar depth variation, as those for the beam scattering effect and the dielectric loss, the attenuation-based condition assessment will be less accurate.

In addition, the performance of the conventional depth correction techniques can also be assessed through Fig. 4. Obviously, the unpredictability of the assessment using the 90th percentile linear regression can be observed. While the regression lines are acceptable for bridge decks in Fig. 4a, d, and e, the deterioration of bridge decks in Fig. 4b, c, and f will be underestimated to different extents. This variability is due to the fact that, for some bridge decks, a part of conductive loss caused by concrete deterioration is misinterpreted as being a result of beam spreading and dielectric loss. Even when the regression lines are acceptable like the ones in Fig. 4a, d, and e, if the conventional depth correction techniques are applied for these decks, the deterioration in the zone of deeper rebars will tend to be exaggerated. This suggests that, separate from the depth correction due to beam scattering effect and dielectric loss, another depth correction is needed for normalizing conductive loss caused by the signal traveling through a conductive concrete.

In addition, the performance of the conventional depth correction techniques can also be assessed through Fig. 4. Obviously, the unpredictability of the assessment using the 90th percentile linear regression can be observed. While the regression lines are acceptable for bridge decks in Fig. 4a, d, and e, the deterioration of bridge decks in Fig. 4b, c, and f will be underestimated to different extents. This variability is due to the fact that, for some bridge decks, a part of conductive loss caused by concrete deterioration is misinterpreted as being a result of beam spreading and dielectric loss. Even when the regression lines are acceptable like the ones in Fig. 4a, d, and e, if the conventional depth correction techniques are applied for these decks, the deterioration in the zone of deeper rebars will tend to be exaggerated. This suggests that, separate from the depth correction due to beam scattering effect and dielectric loss, another depth correction is needed for normalizing conductive loss caused by the signal traveling through a conductive concrete.

3.4. Proposed depth correction method

Based on the findings described in the previous section, a new procedure for depth correction of GPR data is proposed based on the results of this research. The entire process is illustrated in

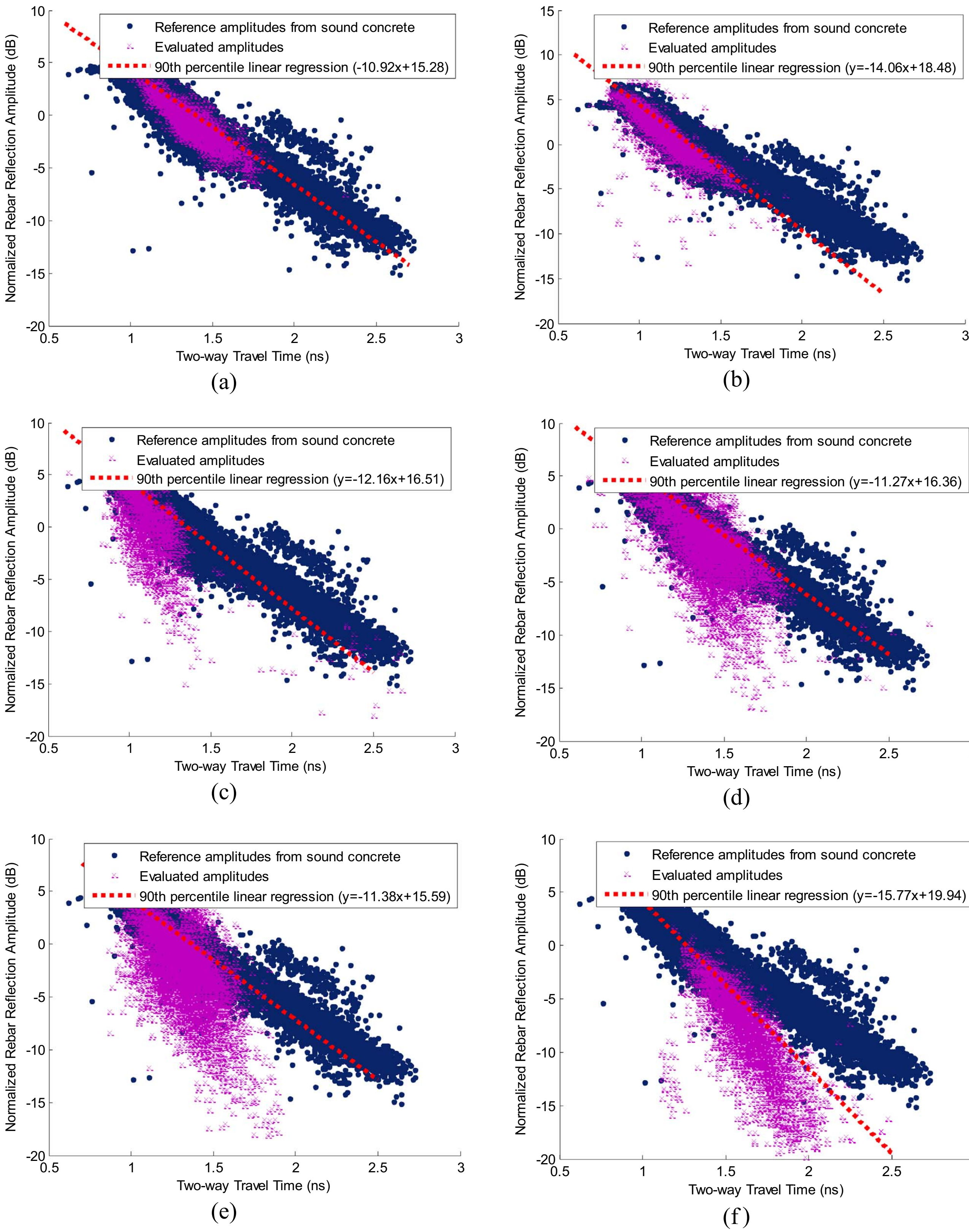

Fig. 4. Effects of deterioration on depth-related amplitudes.

Fig. 5. Basically, the method accounts for three different depth-amplitude effects discussed. Whereas the amplitude reduction caused by the beam scattering effect and dielectric loss can be normalized using the best fit line of the healthy zone in Fig. 6, the attenuation due to an increase of electrical conductivity can be simply normalized by dividing the attenuation obtained after the first step for the TWTT of each rebar. A detailed description and rationale for doing it are provided below.

The first requirement for the proposed method is that all rebar reflection amplitudes have to be normalized by the average direct-

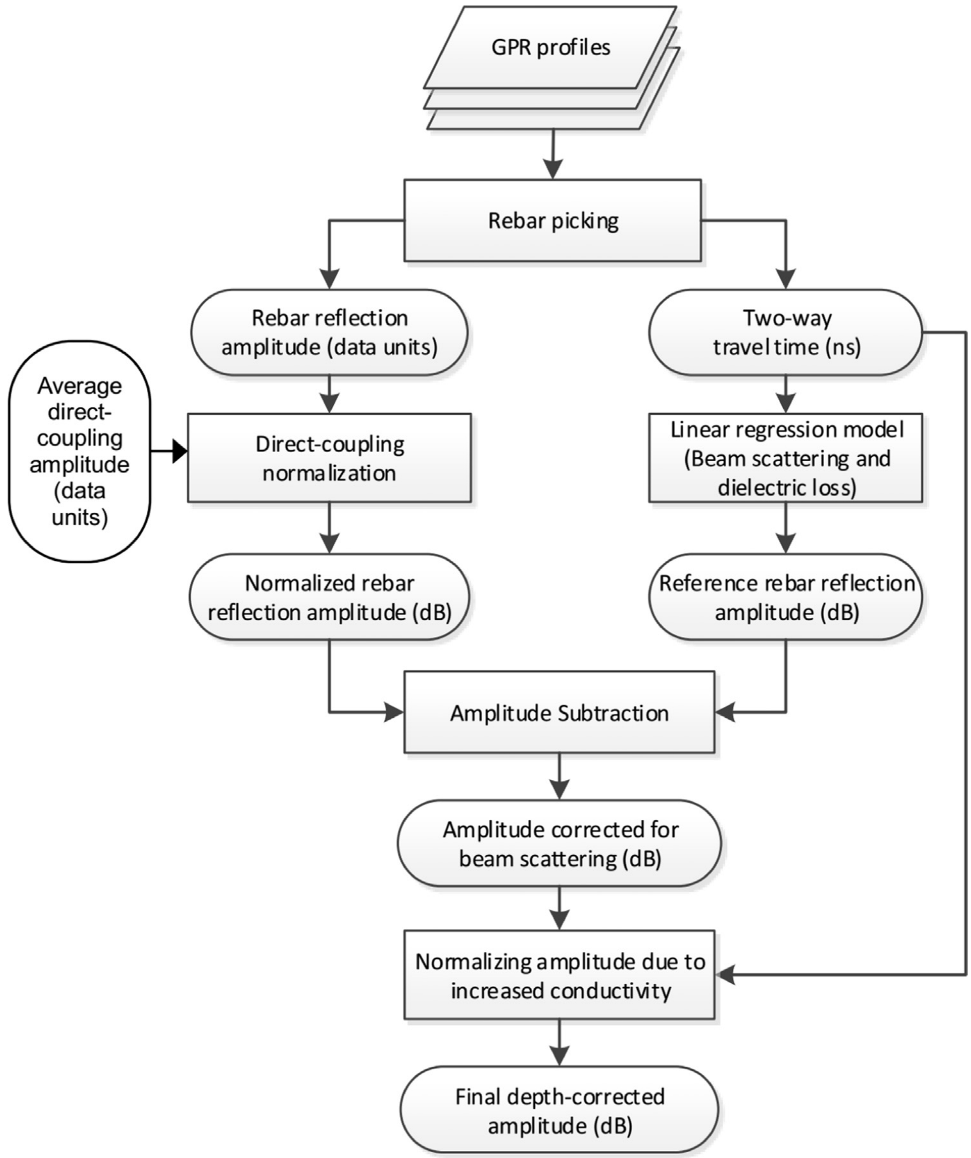

Fig. 5. Proposed procedure for depth correction.

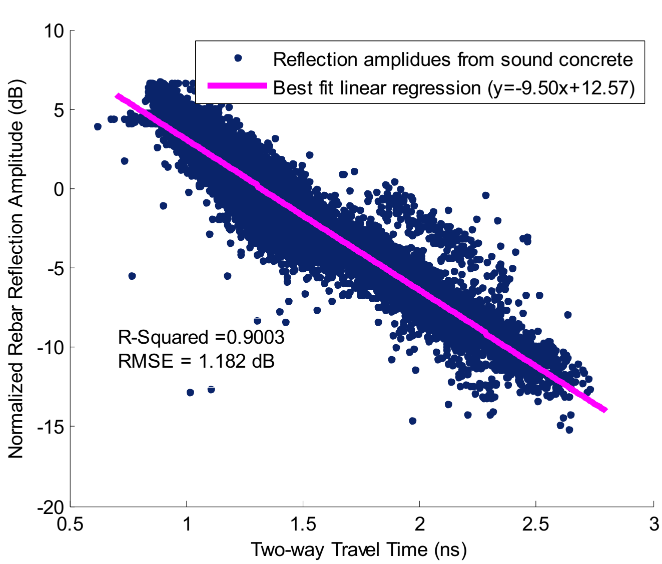

Fig. 6. Depth-amplitude relationship due to beam scattering effect and dielectric loss.

coupling amplitude for each bridge deck. Once the TWTT of a rebar is obtained, based on the regression line in Fig. 6, one will predict the amplitude, if that rebar is associated with sound concrete. This amplitude will serve as a reference and be subtracted from the normalized amplitude obtained in the previous step. If the result is positive, it is likely that the rebar is in sound concrete. Otherwise, it is likely that the concrete is deteriorated.

To clarify, it is worthy to note that the amplitudes in the regression line in Fig. 6 were normalized using the same normalization technique, i.e. the average direct-coupling normalization. As can be seen, the subtraction of the “reference rebar reflection amplitude” from the “normalized rebar reflection amplitude” can be used to express the signal attenuation for a specific rebar in comparison to the expected signal for the same rebar, but in a sound concrete. In addition, it is noted that a jump step appears in the flowchart in Fig. 5 due to the fact that the TWTT is utilized in two different steps. The jump step is when the TWTT is used for normalizing the conductive loss to a TWTT unit (ns).

In a case of negative values, the possibility or severity of deck deterioration should be determined by again taking into consideration the TWTT of a specific rebar. As explained previously, when the conductivity of concrete cover increases, separate from

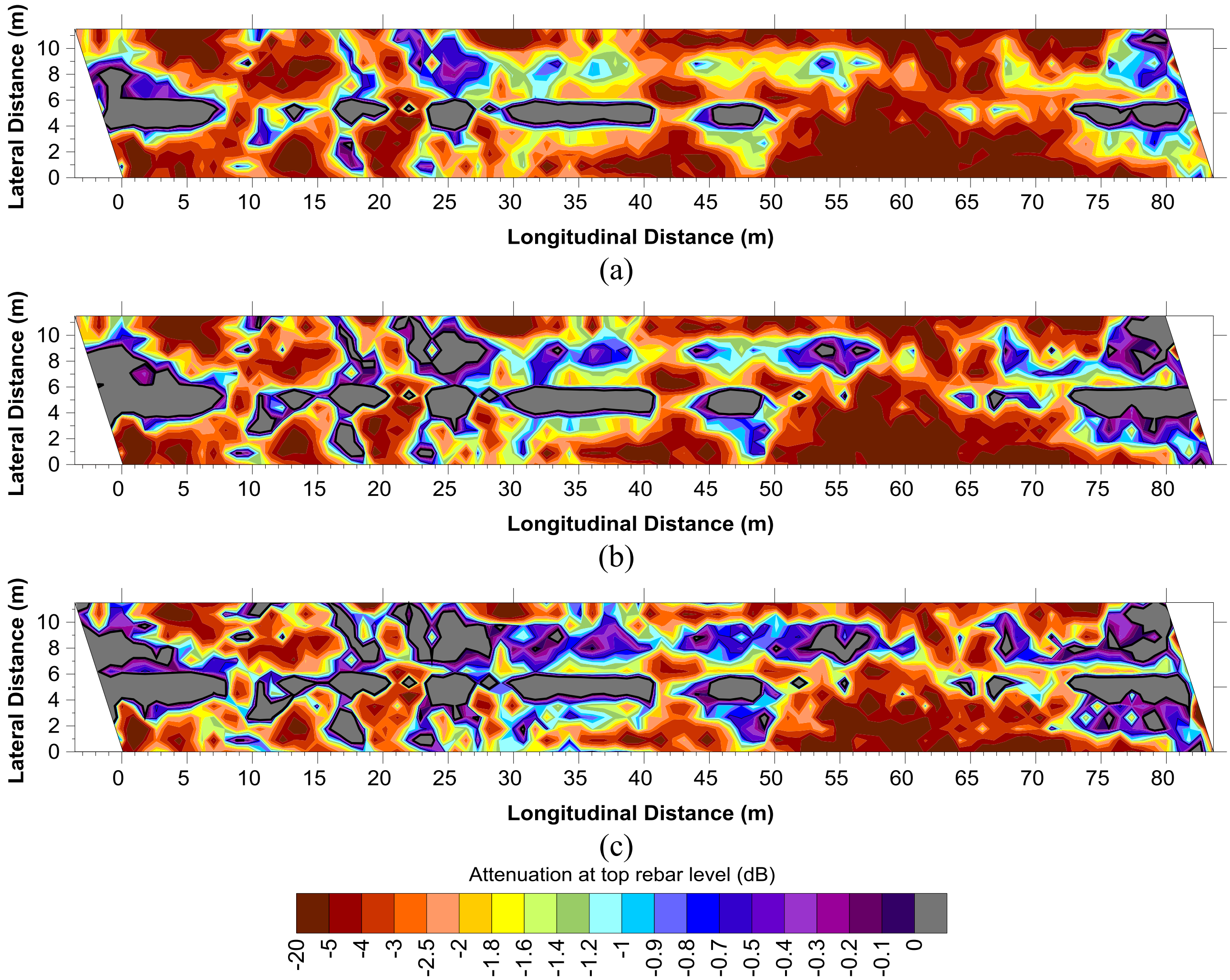

Fig. 7. GPR maps for the Haymarket Bridge deck developed with (a) conventional depth correction technique, (b) depth correction due to beam scattering effect and dielectric loss, and (c) proposed depth correction method.

the beam spreading effect and dielectric loss, the attenuation in the zone of a deeper rebar still tends to be greater than that of a shallow rebar. Therefore, for consistency in assessing concrete deterioration subjected to rebar depth variation, the conductive loss will need to be normalized to a unit of TWTT, e.g. 1 ns. Since the average velocity of EM wave propagation in concrete is about 12.5 cm/ns [15], this TWTT is equivalent to a 6.25 cm cover thickness, without taking into consideration the distance between transmitting and receiving components of the antenna.

The reason for using TWTT to normalize conductive loss of a specific rebar, instead of the cover thickness, is that the time information can be extracted with higher certainty from GPR data than the cover thickness, which would in turn depend on the dielectric constant of concrete. With respect to the computation, if a 10 dB conductive loss is observed for a specific rebar that has a TWTT of 2 ns, it is assumed that each ns of the EM wave travel would be subjected to a 5 dB conductive loss. Although this assumption may not be correct if the chloride concentration and moisture profiles are not constant throughout the cover thickness, such a simplified calculation would still allow the average condition of the concrete cover to be assessed.

4. Case study implementation

In this section, GPR condition maps are developed for two bridge decks using different depth correction approaches. The scatter plots of these decks have been shown in Fig. 4e and f. The maps are later compared with those obtained from other NDE surveys and the differences are discussed. Specifically, three depth correction methods are employed: (1) conventional method with 90th percentile linear regression, (2) depth correction due to beam scattering effect and dielectric loss only; and (3) proposed method for correction of the beam scattering effect, dielectric and conductive loss. While the results from all six bridge decks have been investigated, due to the similarity of the results and space limitation, the remaining four cases are not presented.

4.1. Haymarket Bridge, Virginia

The Rt. 15 over I-66 Bridge in Haymarket, Virginia is one of the bridges surveyed within the LTBP Program. It was constructed in 1979. The bridge deck is on an average 22 cm thick and reinforced by two layers of reinforcing mats. Whereas the bottom mat consists of bare steel bars, the top mat rebars are epoxy-coated. The bridge deck was surveyed in October 2014 using the previously mentioned five NDE techniques. GPR maps developed for the bridge deck using the three depth correction techniques are provided in Fig. 7.

As can be observed, the sound areas (positive amplitude) of bridge deck in Fig. 7a (conventional method) appear smaller than those in Fig. 7b and c. This can be explained through the

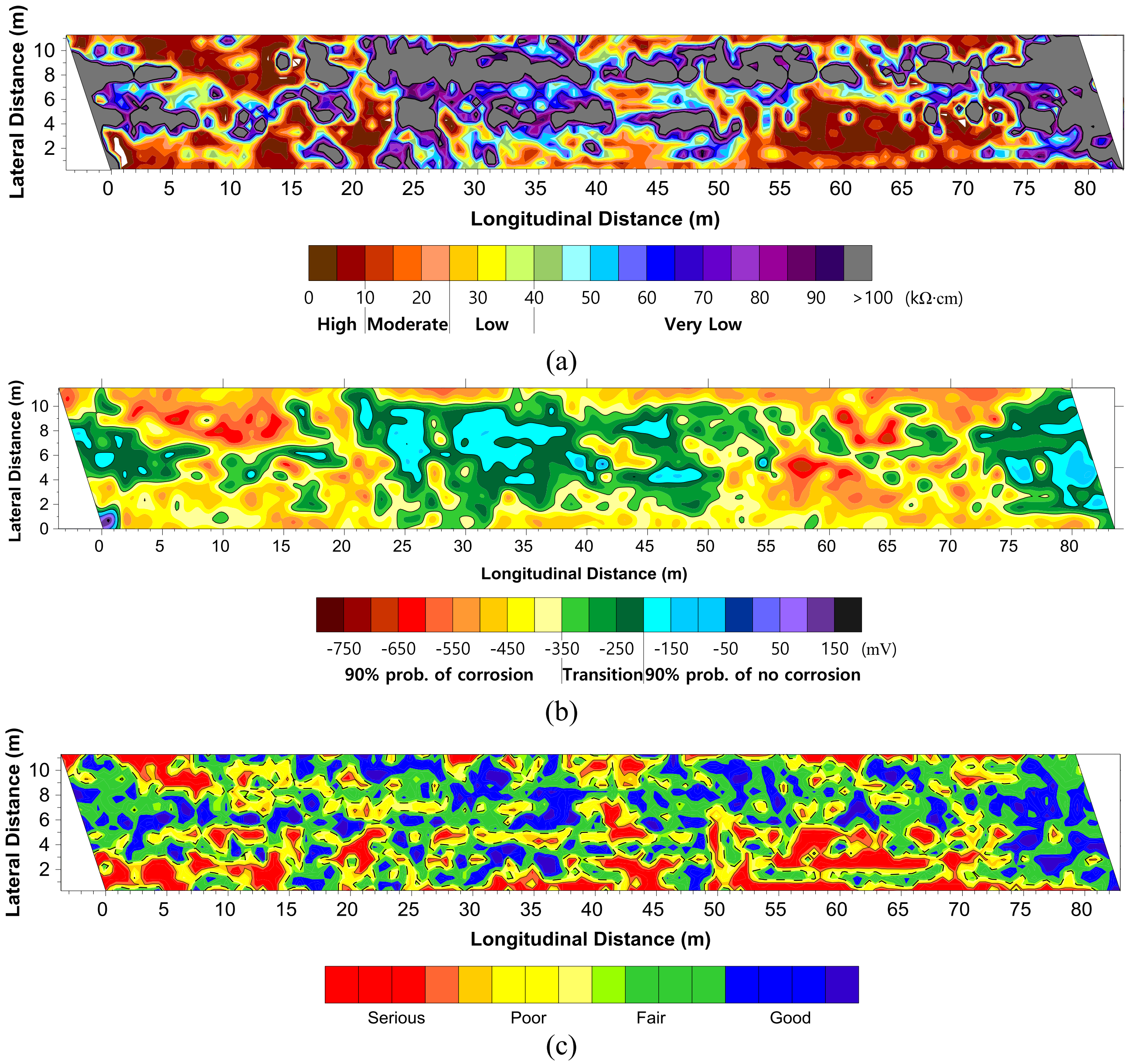

Fig. 8. Condition maps for the Haymarket Bridge deck provided by (a) ER, (b) HCP, and (c) IE.

examination of the scatter plot of the deck in Fig. 4e. In the plot, while the beginning section of the 90th percentile regression line is slightly conservative, the remaining part of the line is in the lower part of the healthy zone. As a result, while the attenuation in the areas with shallow rebars is marginally overestimated, slight deterioration tends to be undetected for areas with deeper rebars using the conventional depth correction method. In addition, whereas the probable areas of concrete deterioration (negative amplitude) are the same in Fig. 7b and c, the condition in Fig. 7c looks less severe. The reason is that in Fig. 7c, after the attenuation is normalized for the beam scattering effect and dielectric loss, the data are again normalized to a common TWTT (1 ns). To be more exact, the unit in Fig. 7c is attenuation per unit TWTT (dB/ns). As the TWTT of most rebars in the deck is greater than 1 ns, the attenuation in Fig. 7c appears less severe than the one in Fig. 7b.

To validate the GPR survey results, the condition maps of the bridge deck obtained from the ER, HCP, and IE surveys are presented in Fig. 8. As can be seen, the deteriorated and sound areas from ER and HCP correlate very well with those of GPR in Fig. 7b and c. As for the IE results in Fig. 8c, delaminated areas appear smaller than deteriorated areas delineated by GPR, ER and HCP. It is not surprising, as it takes time for a delamination to develop after corrosion becomes active.

4.2. *Pohatcong Bridge, New Jersey*

The bridge on Municipal Drive in Pohatcong Township in Warren County, New Jersey, was built in 1978. It is of the same structure type as the described cluster bridges, a bare concrete deck on steel girders. The deck is 25 cm thick and reinforced with two uncoated reinforcing mats. The bridge was surveyed in August of 2014 using three NDE techniques, i.e., GPR, ER, and IE. Fig. 9 provides GPR maps for the bridge deck developed using the three depth correction techniques. The differences between the GPR maps can be easily observed. Whereas a small portion of the deck area in Fig. 9a is sound, Fig. 9b and c suggests that the entire deck is deteriorated. However, the deck condition in Fig. 9c compares the best to the results from other NDE surveys.

The maps created by the three depth correction techniques can be further compared with the ER and IE maps in Fig. 10. As can be

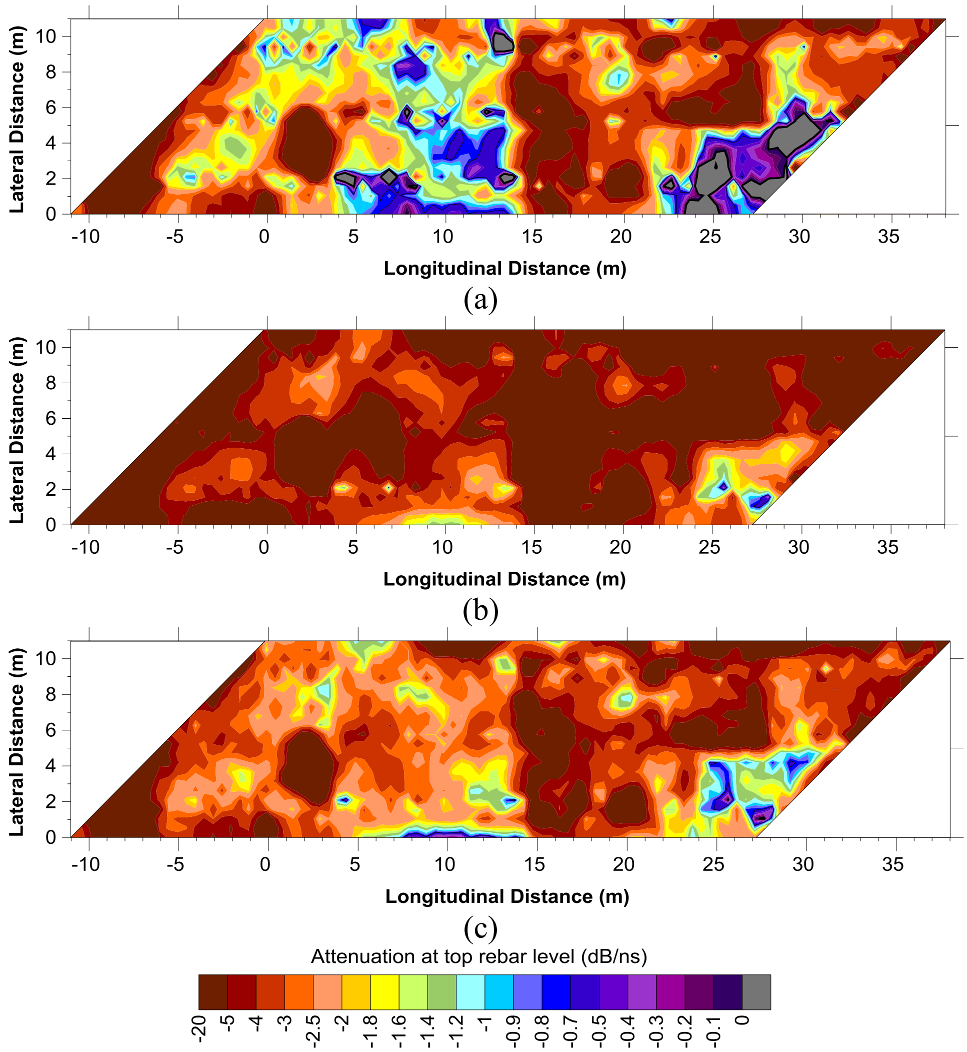

Fig. 9. GPR maps for the Pohatcong Bridge deck developed with (a) conventional depth correction technique, (b) depth correction due to beam scattering effect and dielectric loss, and (c) proposed depth correction method.

seen, there is an agreement between the proposed depth correction technique map and the ER map. They both indicate that the entire deck is deteriorated. The IE map also reveals that delamination is widespread in the deck. The sound area in Fig. 9a appears to be due to the fact that the conventional technique assumes at least 10% of deck area is sound concrete.

5. Discussion

As has been presented, the study concentrated on the development of more complete understanding and consideration of the GPR depth-amplitude effects through an investigation of extensive pool of NDE data for bridge decks. The strong correlation in Fig. 6 shows that up to 90.03% variation of rebar reflection amplitude in sound concrete can be attributed to the variation of concrete cover thickness. The remaining variation may be attributed to other factors, such as rebar size and orientation, concrete mix, moisture content and so forth.

The difference in the results obtained between the conventional and the proposed depth correction techniques can be explained due to the *fuzzy* definition of what constitutes a “sound” concrete in the conventional technique. As has been seen, while the definition is clearly stated in the beginning of this paper based on other NDE techniques, such a definition is vague in the current practice. If the ER map of the Pohatcong Bridge deck in Fig. 10a is investigated, it is easy to recognize that the deck area with the best condition has the ER measurement of 40 kΩ cm, or higher. According to [12], this value corresponds to a concrete with a moderate to high corrosion risk. However, such a concrete will be considered “sound” and be employed as the reference in the conventional depth correction technique.

6. Conclusions

Accounting for the depth-amplitude effects is one of the most important tasks in the condition assessment of concrete bridge decks from GPR data. Theoretically, three mechanisms may govern the relationship: geometric, dielectric and conductive losses. However, through an extensive study of GPR and other NDE technology data, only dielectric and conductive losses were found to be dominant. Once the nature of each mechanism has been clearly understood and quantified, a new depth correction procedure was proposed. Compared to the current practices, the proposed technique significantly improves the accuracy of GPR based condition assessment of concrete bridge decks, as illustrated by the results for the two bridges. As the technique was developed using a large volume of GPR data from representative bridge decks, it is ready for practical implementation. However, since the data

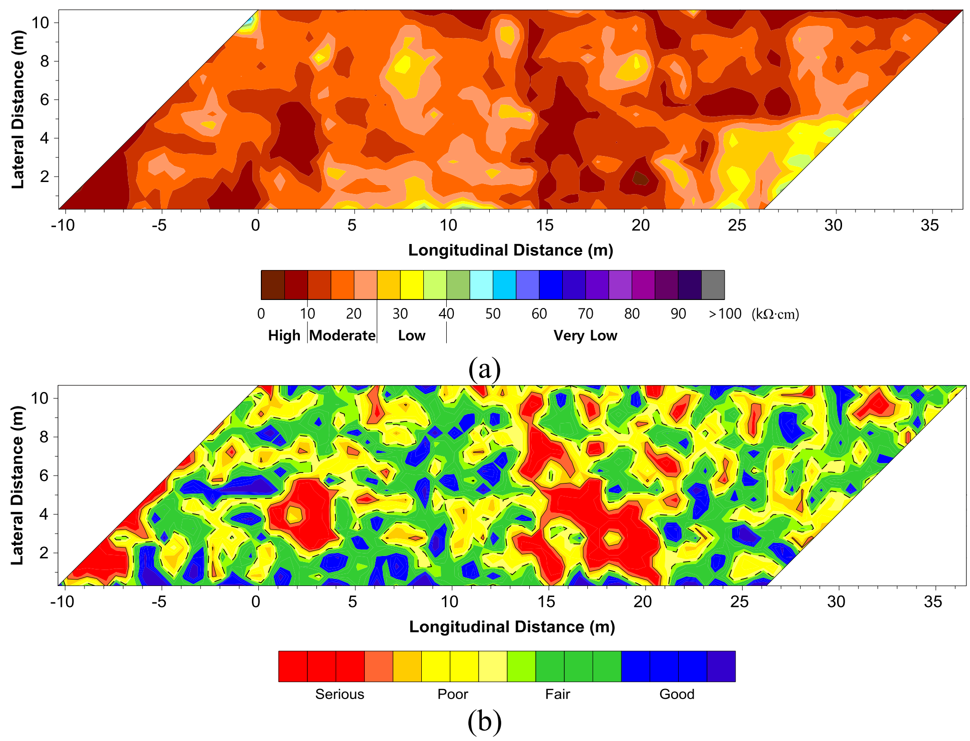

Fig. 10. Condition maps for the Pohatcong Bridge deck provided by (a) ER, and (b) IE.

used were only for bare bridge decks, the depth-amplitude function presented in this paper is only applicable to investigations of such decks. Additional depth-amplitude functions will be needed for bridge decks with different overlay types. The proposed method will not be applicable without such pre-determined depth-amplitude relationships.

Acknowledgements

The authors sincerely acknowledge the support of the Federal Highway Administration through the LTBP Program. The authors are also grateful to the Virginia Department of Transportation (VDOT) and Warren County Department of Public Safety for their cooperation in providing access to the bridges presented in this study. Finally, the authors are grateful to Kenneth Lee, Shane Mott and Insung Hwang from Rutgers' Center for Advanced Infrastructure and Transportation (CAIT) for their help during the data collection.

References

[1] Parrillo R, Roberts R, Haggan A. Bridge deck condition assessment using ground penetrating radar. Proceedings of the ECNDT, Berlin, German. 2006 Sep; 2526:112.

[2] Barnes CL, Trottier JF. Effectiveness of ground penetrating radar in predicting deck repair quantities. J Infrastruct Syst 2004;10(2):69–76.

[3] Barnes CL, Trottier JF, Forgeron D. Improved concrete bridge deck evaluation using GPR by accounting for signal depth–amplitude effects. NDT E Int 2008;41(6):427–33.

[4] Tarussov A, Vandry M, De La Haza A. Condition assessment of concrete structures using a new analysis method: ground-penetrating radar computer-assisted visual interpretation. Construct Build Mater 2013;38:1246–54.

[5] Dinh K, Zayed T, Romero F, Tarussov A. Method for analyzing time-series GPR data of concrete bridge decks. J Bridge Eng 2014;20(6):04014086.

[6] Romero FA, Barnes CL, Azari H, Nazarian S, Rascoe CD. Validation of benefits of automated depth correction method: improving accuracy of ground-penetrating radar deck deterioration maps. Transportation research record. J Transp Res Board 2015;1(2522):100–9.

[7] Dinh K, Zayed T, Moufti S, Shami A, Jabri A, Abouhamad M, Dawood T. Clustering-based threshold model for condition assessment of concrete bridge decks with ground-penetrating radar. Transportation research record. J Transp Res Board 2015;1(2522):81–9.

[8] Varnavina AV, Khamzin AK, Sneed LH, Torgashov EV, Anderson NL, Maerz NH, Boyko KJ. Concrete bridge deck assessment: relationship between GPR data and concrete removal depth measurements collected after hydrodemolition. Construct Build Mater 2015;99:26–38.

[9] Geophysical Survey Systems (GSSI).RADAN 7 manual, Salem, NH, 2012.

[10] Feynman RP, Leighton RB, Sands M. The Feynman Lectures on Physics, Vol. 2: Mainly Electromagnetism and Matter. . Addison-Wesley; 1979.

[11] ASTM C876 – 09. Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete. Annual Book of ASTM Standards, 3.02. West Conshohocken, PA: ASTM International; 2009.

[12] Feliu S, Gonzalez JA, Andrade C. Electrochemical methods for on-site determinations of corrosion rates of rebars. InTechniques to assess the corrosion activity of steel reinforced concrete structures; 1996 Jan. ASTM International.

[13] Gucunski N, Yan M, Wang Z, Fang T, Maher A. Rapid bridge deck condition assessment using three-dimensional visualization of impact echo data. J Infrastruct Syst 2011;18(1):12–24.

[14] ASTM D 6087–08. Standard Test Method for Evaluating Asphalt-Covered Concrete Bridge Decks Using Ground Penetrating Radar. West Conshohocken, PA: Designation D6087-08, ASTM International; 2008.

[15] Laurens S, Balayssac JP, Rhazi J, Klysz G, Arliguie G. Non destructive evaluation of concrete moisture by GPR technique: experimental study and direct modeling. NDT-CE 2003 16;3:16–9.