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

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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

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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