Adapting a Ground Coupled GPR Threshold Model for Use with Air Coupled GPR Systems

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Abstract
In order to properly repair the thousands of bridge decks in poor condition throughout our Nation, it is crucial that they undergo accurate and complete inspections, internally as well as externally. Current inspection techniques, like visual inspection, lack the ability to obtain detailed information inside of the deck, and can lead to an inaccurate assessment. Ground penetrating radar is a commercially available technology which can examine the internal composition of the deck at highway speeds. However, due to the lack of a threshold, necessary to distinguish healthy from corroded areas, the assessments must be completed by experienced practitioners. Previous work has demonstrated a method for establishing a threshold using hand operated, ground coupled GPR equipment. The research presented in this paper seeks to extend these thresholding concepts to high speed, air coupled GPR systems. Three in-service bridge decks, and four sawcut slabs of a bridge deck removed from service were assessed with a 2GHz air coupled antenna. Once the data from each deck were extracted at the rebar level and depth corrected, descriptive statistics, like the mean and skew were computed for each. These statistics were then multiplied together for each deck and plotted against actual deterioration quantities computed using half-cell potential measurements previously obtained. An 88% correlation coefficient was computed for these quantities, showing promise in these initial stages of the threshold model development.

Keywords: Bridge decks, deterioration, corrosion, ground penetrating radar (GPR), half-cell potential (HCP), thresholds

1. Introduction
As the infrastructure in the United States continues to age, researchers are working to develop new methods and adapt commercially available technologies in order to properly evaluate the infrastructure’s internal condition. Bridge decks in particular are a target for this research since they are currently evaluated by deficiencies visible only on the outer surface of the deck. A complete (internal and external) assessment of bridge decks, and any form of infrastructure, is beneficial to transportation agencies because they will be able to locate and properly repair damage throughout the structure.

In recent years, researchers have found that nondestructive evaluation (NDE) techniques like ground penetrating radar, potential methods, and sounding have been able to pinpoint the location and extent of damage associated with corrosion of the reinforcing steel within reinforced concrete bridge decks [1]. Since corrosion of the reinforcing steel is the most common cause of bridge deck deterioration, researchers work to detect a corrosive environment (using potential methods) and delaminations (using sounding techniques) with these methods, as they are a result of this type of deterioration. However, a major drawback of these methods is that they require lane closures since they are slow, point-by-point methods.

One major benefit that ground penetrating radar has above potential and sounding methods, is its ability to collect data at highway speeds without disrupting traffic. This is
completed using an air coupled or horn antenna, which is mounted onto a vehicle and sits roughly 18” above the deck’s surface. Currently, this method is not used as a sole assessment technique because unlike potential and sounding methods, there lacks an available threshold which can quickly and accurately distinguish healthy from corroded areas of the deck.

2. Previous work

In the past recent years, researchers have worked toward developing methods and models so that GPR can be used as a sole assessment technique. A roadmap, displaying the steps which have been taken towards this goal is as follows:

1. Understand the relationship between GPR and the aforementioned consequences of rebar corrosion by correlating radar results with those of other NDE techniques like potential and sounding.
2. Using the results of step (1), select the mechanism and its associated NDE detection technique which correlates the best with GPR.
3. Use GPR and the technique selected in step (2), to develop a tool which can be used to assess future bridge decks using radar alone.

Many scholars have found substantial relationships between radar and the various outcomes of rebar corrosion. For example, nine bridge decks were analyzed with half-cell potential, chain drag and a 1GHz air coupled GPR system [2]. Deterioration quantities as a percentage of the deck’s surface area using each method were determined for each deck. The average difference calculated between GPR and HCP, and GPR and chain drag for all nine decks was -2.2% and -1.7%, respectively.

The above case study highlighted substantial results found when using an air coupled GPR system. However, various studies have been conducted using ground coupled GPR systems as well. For example, it was found in a laboratory study that a 1.5GHz ground coupled system was able to detect artificially placed delaminations larger than 7mm in diameter [3]. Also in a laboratory study, a report indicated that after the corrosion process of a specially constructed reinforced concrete slab was initiated, the rebars became less visible in the GPR data as the half-cell potential measurements decreased [4]. An in-service bridge deck in Maine evaluated with a 1.5GHz ground coupled antenna and chain drag indicated deterioration in the same areas [5]. Similarly, good correlation was found between a 1.5GHz ground coupled antenna and half-cell potential tests of three in-service decks [6].

The authors of this paper have also completed various in-field and laboratory investigations using a ground coupled GPR system with a center frequency of 2.6GHz, half-cell potentials and impact echo. For example, four sawcut slabs extracted from a bridge deck removed from service were subjected to testing using these technologies. The data from each method were compared spatially, which resulted in GPR and HCP indicating the same areas of deterioration for over 90% of the surface area, while GPR and impact echo agreed for about 80%. The results of this and other studies, including those mentioned in the previous paragraphs led the authors to acknowledge the idea that GPR is better correlated with half-cell potentials or active corrosion [7].

In an effort to develop a tool which can be used to detect bridge deck deterioration using radar alone, the authors of this paper set out to collect data from four in-service bridge decks, in addition to, acquiring data sets from Infrasense, Inc. For these cases, in addition to the case study
described in the previous paragraph, the HCP data was analyzed to determine actual deterioration quantities of each deck, and the GPR data, whose information was extracted at the rebar level, were assessed with statistics to characterize each deck. These quantities were compared for each deck in order to develop a preliminary tool which can assess bridge decks with radar alone, if a ground coupled system is utilized [8].

The research presented in this paper seeks to adapt this preliminary tool to air coupled systems, as these can be used to collect data at highway speeds. The procedure which was used to analyze the data and create the preliminary tool will be described below, in addition to, a comparison between ground and air coupled system results.

3. Data analysis

1GHz and 2GHz air coupled GPR data were collected from the three bridge decks presented in [9], and the sawcut slabs presented in [7] by Infrasense, Inc. The 2GHz air coupled results will be presented in this paper, and those data sets were analyzed in the following manner:

(1) Two channels (Channel 1 and 2) were used to collect data for each of the bridge decks, where Channel 1 was dedicated to the collection of the 1GHz data and Channel 2 for the 2GHz data. Therefore, each of the data files needed to be split, so that each channel could be worked with separately. Also, the air and plate files were split for use in upcoming steps.

(2) Data were collected along each lane of travel in roughly 3foot increments. Due to this orientation, the files collected in one lane needed to be reversed to meet the direction of data collected in the opposing lane.

(3) A calibration file was then created from the 2GHz air and plate files. This was created to subtract the surface and complete a dielectric calculation.

(4) All of the data files were processed using the calibration file created in Step 3.

(5) During data collection of each deck, a constant gain was applied. This gain was removed so that these data sets can be compared to others in the future.

(6) “Pick” all of the data points associated with the rebar layer. Unlike the ground coupled data, where information from each rebar location can be extracted individually, the information at the rebar level in the air coupled data must be selected in a layer. This is because the antenna is high above the surface, as opposed to sitting on the surface, and therefore averages results from multiple rebar along each point of travel.

(7) The data is then organized and depth corrected according to [10]. This is to correct for any low rebar amplitudes, associated with deeper rebar placement during construction, as opposed to corrosion.

Due to the condition of the data collected from the sawcut slabs, only Steps 5-7 were executed.

4. Results

4.1 Spatial comparison of ground and air coupled systems

The preliminary analysis of the processed data was completed by contour plotting the air coupled data from each deck, and then comparing these plots to those previously created using the ground coupled data. The color contour plots below display the results of the four sawcut slabs removed
from service. The plots of the 2GHz horn data, and 2.6GHz ground coupled data mostly agree, however few discrepancies exist, especially in the upper right corner possibly due to the following reasons.

(1) Some edge effects seem to be prevalent when collecting data with the horn antenna due to placement of the antenna.

(2) Plexiglas was used to cover the spalled areas (indicated by the white and black “patches”) so the cart carrying the antenna could travel over the entire surface. This could have interfered with the data collected in these areas.

(3) An air gap located along the x-direction at y=300cm could be the cause of disagreement at this location.

A comparison of the ground and air coupled data collected from the three in-service bridge decks can be found in [11].

Figure 1a. 2GHz Horn 1b. 2.6GHz Ground coupled contour plots of the sawcut slabs
4.2 Histogram comparison of ground and air coupled systems

The authors were inspired to develop the preliminary model in [8], through the formation of histograms created using the depth corrected rebar level amplitudes of each deck. The “Corroded Bridge Deck” histogram displayed in that paper, was created from the ground coupled, depth corrected rebar amplitudes of the sawcut slabs in Figure 1b. That histogram is recreated below (Figure 2b) with its associated histogram created from the 2GHz horn, depth corrected rebar amplitudes (Figure 2a).

By observing these histograms, one could notice that they have very similar shapes, and features such as the mean and skew (quantified in Table 1). The air coupled histogram is more “filled out” probably because a significantly larger amount of data was collected using the horn antenna. Also, referring to Table 1, it is noticeable through the calculation of the skew and mean of the horn data, both of these quantities decreased (became more negative). This may be due to the fact that since the amplitudes at the rebar level are selected in a layer, very corroded areas which were not clear in the ground coupled data, were selected in the air coupled data.
5. Model development

Similar to that of the model developed from the ground coupled data, descriptive statistics like the skew and mean were computed for each radar data set. These two statistics were then multiplied together to characterize the condition of the deck with the GPR data. The actual deterioration quantities, based on the HCP data were taken from [8]. A comparison of the newly computed air coupled statistics to the ground coupled statistics can be found in Table 1.

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Sawcut Slabs</th>
<th>Bridge A</th>
<th>Bridge B</th>
<th>Bridge C</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Deteriorated (% HCP &lt; -0.35V)</td>
<td>38.19</td>
<td>54.39</td>
<td>46.35</td>
<td>71.04</td>
</tr>
<tr>
<td>Ground Coupled Mean</td>
<td>-1.80</td>
<td>-2.70</td>
<td>-2.11</td>
<td>-5.71</td>
</tr>
<tr>
<td>Ground Coupled Skew</td>
<td>-0.96</td>
<td>-1.19</td>
<td>-1.64</td>
<td>-0.87</td>
</tr>
<tr>
<td><strong>Ground Coupled Mean*Skew</strong></td>
<td>1.73</td>
<td>3.19</td>
<td>3.45</td>
<td>4.97</td>
</tr>
<tr>
<td>Air Coupled Mean</td>
<td>-0.94</td>
<td>-5.11</td>
<td>-3.42</td>
<td>-7.15</td>
</tr>
<tr>
<td>Air Coupled Skew</td>
<td>-1.17</td>
<td>-1.01</td>
<td>-0.93</td>
<td>-0.86</td>
</tr>
<tr>
<td><strong>Air Coupled Mean*Skew</strong></td>
<td>1.11</td>
<td>5.16</td>
<td>3.19</td>
<td>6.12</td>
</tr>
</tbody>
</table>

By observing the computed means, one can notice that if the decks were placed in an order due to this quantity, it would be the same for both radar systems. If the same observation was made for the skew, and the skew x mean, one would notice that Bridge A and Bridge B have switched “order” in comparison to those quantities computed using the ground coupled data. However, the new “order” based on the computations of the air coupled data seem to be more in
line with the actual deterioration quantities. This could be because the air coupled antenna “sees” more of the deck during data collection.

In order to fully develop the preliminary model, the skew x mean of the air coupled data and the actual deterioration quantities were plotted (Figure 3) in a similar manner to that found in [8]. In this case, the correlation coefficient is slightly lower than that of the ground coupled preliminary model. This, again, could be because the data points are selected in a layer, extracting data from severely corroded locations which may have been unclear in the ground coupled data. This model can be used to immediately determine the amount (%) a deck is corroded, in addition to the GPR threshold used to separate corroded from healthy areas. A full, step-by-step guide describing exactly how to use this preliminary model can be found in [8].

![2GHz Air Coupled Bridge Deck Statistical Model](image)

\[ y = 5.931469x + 29.391877 \]
\[ r^2 = 0.883395 \]

Figure 3. Bridge deck statistical model for 2GHz horn antenna

6. Conclusions

This paper has presented the beginning development of a tool, friendly to transportation agencies, which can quickly and accurately assess bridge decks without disrupting traffic. The necessity of a tool such as this one is crucial because it will: decrease the cost of inspections as data can be collected and processed in minutes as opposed to days; provide agencies the ability to assess more than one deck per day, and more often than every two years; accurately determine the location and extent of damage within a bridge deck as opposed to only on the surface; reduce the cost of congestion because lane closures are not necessary during data collection. As this is a preliminary model, the authors are prepared to collect and analyze many more data sets to add to this model.

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References