Ground Penetrating Radar (GPR): Using Radio Waves to Detect Salt on Asphalt Overlaid Bridge Decks

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ABSTRACT

As part of bridge maintenance, evaluating deterioration in asphalt overlaid concrete bridge decks is crucial in determining the timing and nature of any maintenance. Chloride contamination caused by de-icing salt is one of the primary contributors to bridge deck deterioration in northern climates. Early detection can trigger proactive maintenance rather than more expensive, reactive rehabilitation. Ground Penetrating Radar (GPR) technology is an efficient and reliable testing method that collects data to evaluate deterioration in asphalt overlaid concrete bridge decks. When comparing the results of the GPR evaluation to that of ASTM D6087 and traditional test methods (Chloride samples, AC resistance, and corrosion potential), the results proved more accurate when compared to ASTM D6087, and correlated well with traditional methods.

GPR can identify and quantify the chloride contamination by looking for reductions in the amplitude of the returning signal due to attenuation. Attenuation is affected by the conductivity (chloride content) of the concrete. The challenge is that the amplitude of the returning signal is also affected by geometric spreading of the signal. A method to account for geometric spreading (by normalizing the amplitude to the 90th percentile of the data) has been developed and is extensively used on bare concrete decks, but less work has been done on data correction for asphalt overlaid bridge decks. On asphalt overlaid bridge decks, the GPR signal must pass through both the asphalt and concrete, both of which have different electromagnetic material properties. Consequently, this produces less reliable results due to the addition of amplitude variability caused by inconsistent signal reflection at the asphalt/concrete interface. To address this, the amplitude was corrected for geometric spreading using the 90th percentile method and applying Fresnel's Law to correct for the variability in the asphalt/concrete interface reflection.

A total of five structures in Ontario with asphalt overlays, waterproofing membranes, and epoxy rebar were tested in 2020 using GPR to determine chloride contamination. The results from the proposed GPR method were compared to the traditional test methods, and to the analysis method specified in ASTM D6087. The results of this GPR approach suggested that accounting for geometric spreading, in conjunction with interface reflection correction, not only correlates with the traditional test methods, but produces more accurate deterioration mapping than ASTM D6087. This increased accuracy allows for better decision making on the timing and nature of any recommended bridge repairs, leading to improved cost savings over the lifespan of the bridge.

INTRODUCTION

In the United States alone, over $125 billion needs to be invested to address bridge deficiencies (ASCE 2021). With this large cost, it is important to effectively evaluate damage and prioritize repairs. Bridge owners have several inspection techniques to evaluate damage and deterioration of bridge decks. Many of these inspection techniques are suitable for exposed concrete bridge decks or decks without epoxy coated rebar; however, determining the condition of the underlying concrete on asphalt overlaid bridge decks or decks with epoxy coated rebar can be challenging. Ground Penetrating Radar (GPR) is a non-destructive test (NDT) that can provide data about the condition of the underlying concrete without damaging the overlying asphalt or waterproofing membrane.

GPR systems consist of an antenna and a control unit. They work by using electromagnetic (EM) pulses to detect subsurface features. The antenna emits an EM pulse which reflects when there is a sudden change in EM pulse velocity. The reflected EM pulse returns to the antenna where the two-way travel time (TWTT) and the reflection amplitude are recorded. Figure 1 shows the typical pulse paths for GPR on an asphalt overlaid deck.

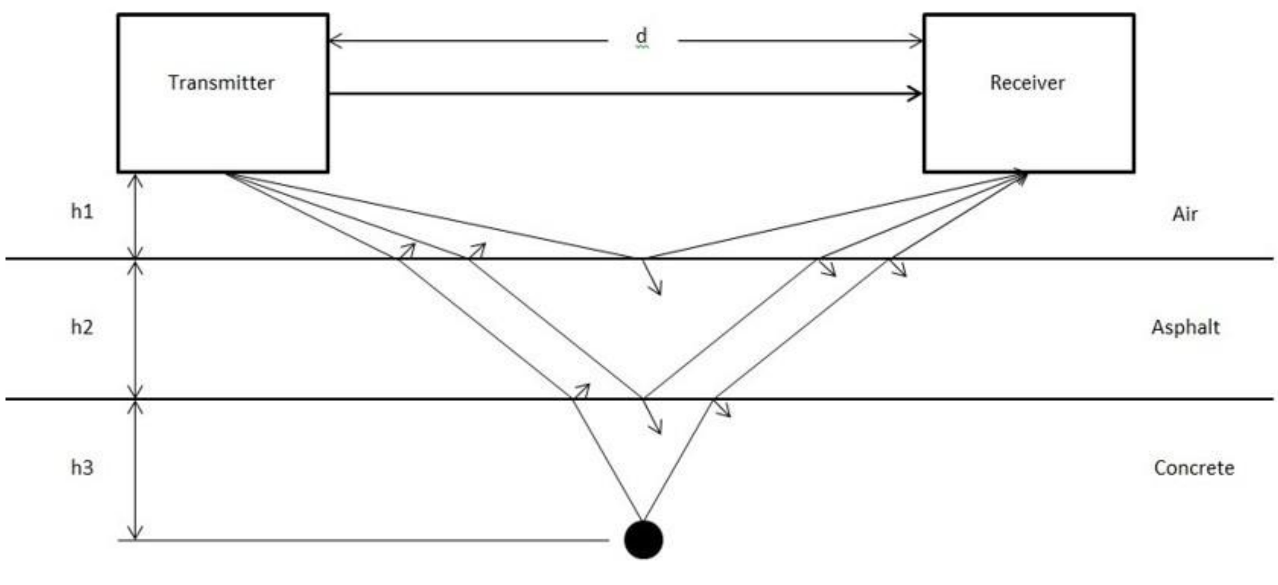

Figure 1: GPR Wave Paths

GPR is used to detect chloride contamination in concrete by looking for a reduction in the amplitude of the returning signal that reflects off the rebar. Figure 2 shows what the rebar reflection looks like with and without chloride contamination.

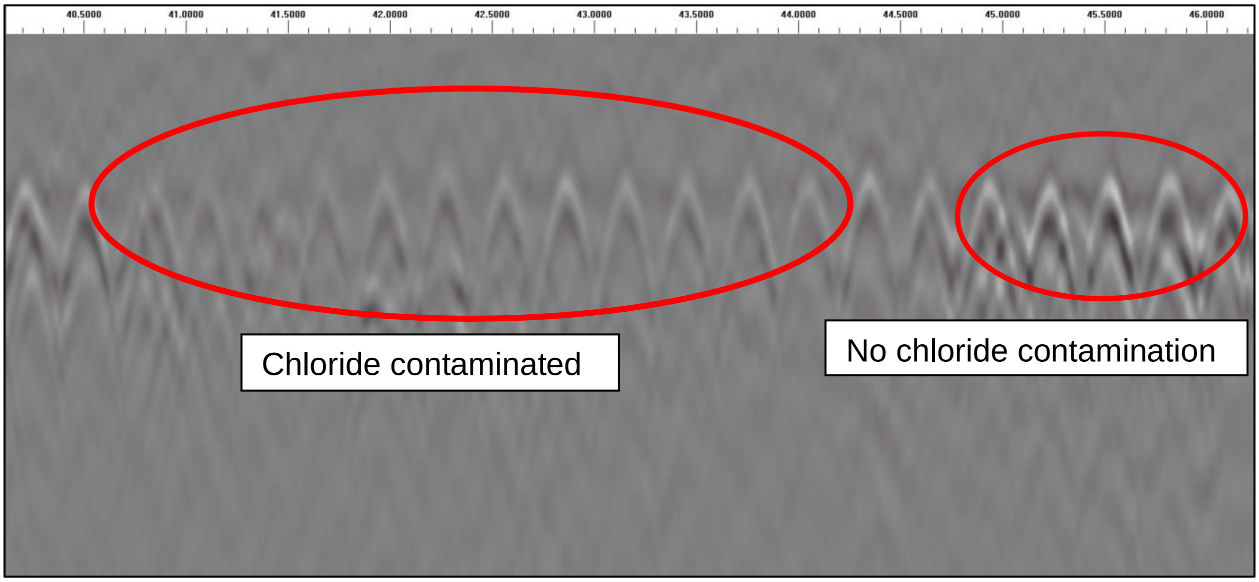

Figure 2: Sample of Potential Deteriorated Rebar

ASTM D6087 is the standard that deals with identifying chloride contamination for concrete structures with an asphalt overlay. ASTM D6087 includes two methods for detecting chloride contamination:

1. Look for reductions in the amplitude of the reflection from the deck bottom.
2. Look for reductions in the amplitude of the reflection at the top layer of rebar.

Analysis method two was used for this work. Method two uses the maximum recorded amplitude as a reference point for the corrosion threshold. Any reading below the threshold is considered contaminated. Typically, the threshold is 6 – 8 dB below the maximum recorded amplitude.

The underlying assumption of ASTM D6087 is that any reduction in rebar amplitude, from the maximum recorded amplitude, can only be due to chloride contamination. There are two main sources of inaccuracy with this assumption and methodology. The first is using the maximum amplitude as a reference point for the threshold value. The size of the data sets used in GPR analysis are often in the thousands, if not 10’s of thousands of data points. This means the chances of outlying data points is high. The consequence of this is the maximum data point may not be representative of the true condition of the structure and more importantly may not be replicable between tests, resulting in inaccurate results. The second source of inaccuracy is the method does not account for the effects of variability in the signal amplitude from sources such as variable asphalt thickness, variable rebar cover, or variable reflection at the asphalt concrete interface. These inaccuracies can lead to significant errors in the estimated area of chloride contaminated concrete.

STRUCTURE DESCRIPTION

Five structures in Ontario were analyzed using ASTM D6087 and a modified version of ASTM D6087 (Modified ASTM). The five structures had the same basic design parameters:

- Lengths varied from 20.1 m to 599.7 m and the widths were consistently 17.75 m.
- 90 mm design thickness of asphalt pavement on top of a hot rubber waterproofing membrane and protection board,
- 225 mm thick concrete deck,
- Epoxy coated rebar, and
- The superstructure, including asphalt and waterproofing membrane, were installed in 2002, making them 18 years old at the time of testing.

DATA COLLECTION

The GPR system used to complete the testing was manufactured by Geophysical Survey Systems Inc. (GSSI). It consisted of a SIR-4000 data acquisition system, a wheel-mounted distance measuring instrument (DMI), and a ground coupled antenna with a central frequency of 1,600-MHz (model 51600S). The 1,600 MHz antenna was set to collect at 8 nanoseconds, the transmission rate for the collection was set to 100 kHz, and data was collected at a scan rate of 300 scans per metre. The GPR data was collected in straight lines in both the transverse and longitudinal directions for each of the five bridges. Photo 1 show the GPR unit used to collect the data.

Photo 1: GPR Unit Used for Data Collection

The GPR data was processed using RADAN 7.0. The data was migrated to single points before being “picked”. The data “picks” were exported to a Comma Separated Values (CSV) file so they could be analyzed.

A sample screen capture identifying the asphalt layer is presented in Figure 3.

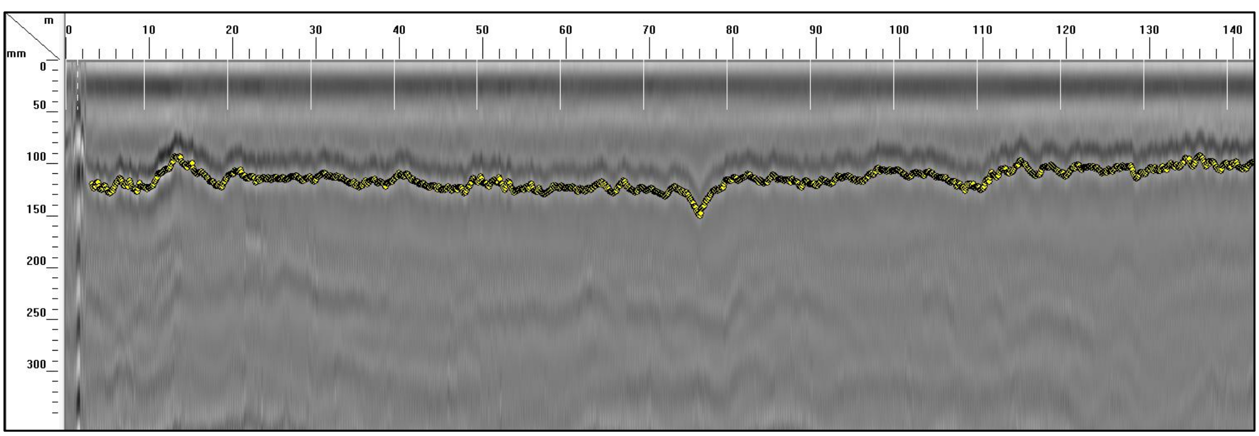

Figure 3: Sample of Asphalt Layer

A sample screen capture of identifying the rebar is presented in Figure 4.

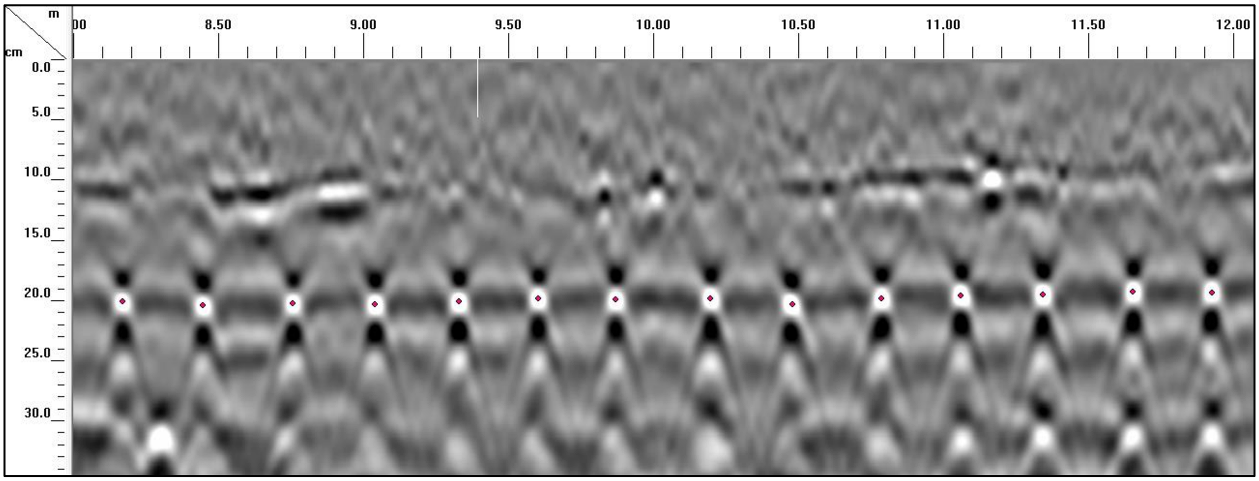

Figure 4: Sample of Rebar Selection

DATA ANALYSIS

ASTM METHODOLODGY (ADJUSTMENT TO MAXIMUM AMPLITUDE)

To investigate whether "outlying" data points were a concern, the amplitude of the 20 largest data points, for each structure were plotted, see Figure 5 to 8. As can be seen the top few data points vary significantly from the subsequent data points. To produce results that were more statistically robust, the largest data point that did not visually appear to be an outlier was taken as the "maximum" recorded amplitude and the threshold was based off that point. The "maximum" data points used in the analysis are denoted as red triangles in Figure 5 to 8.

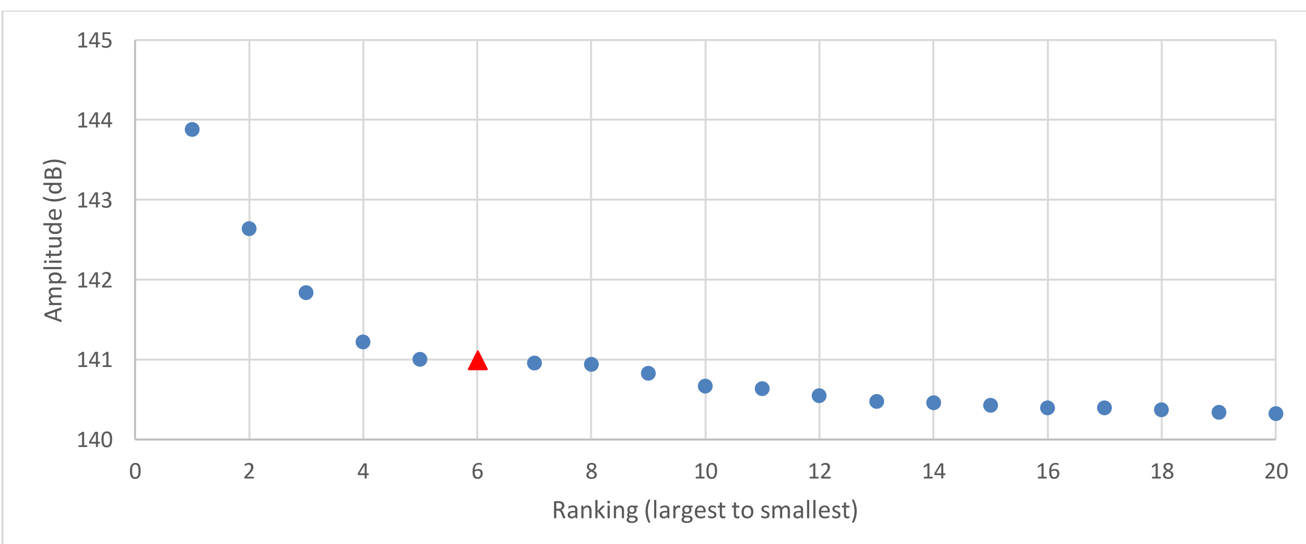

Figure 5: Structure 1, 20 Largest Data Points in the Data Set

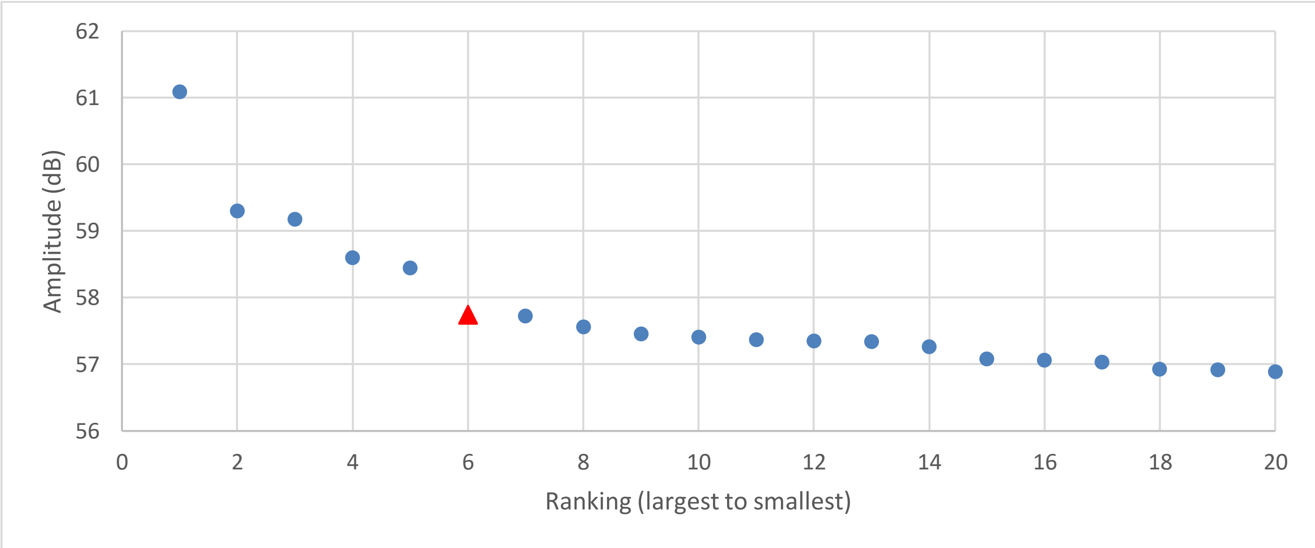

Figure 6: Structure 2, 20 Largest Data Points in the Data Set

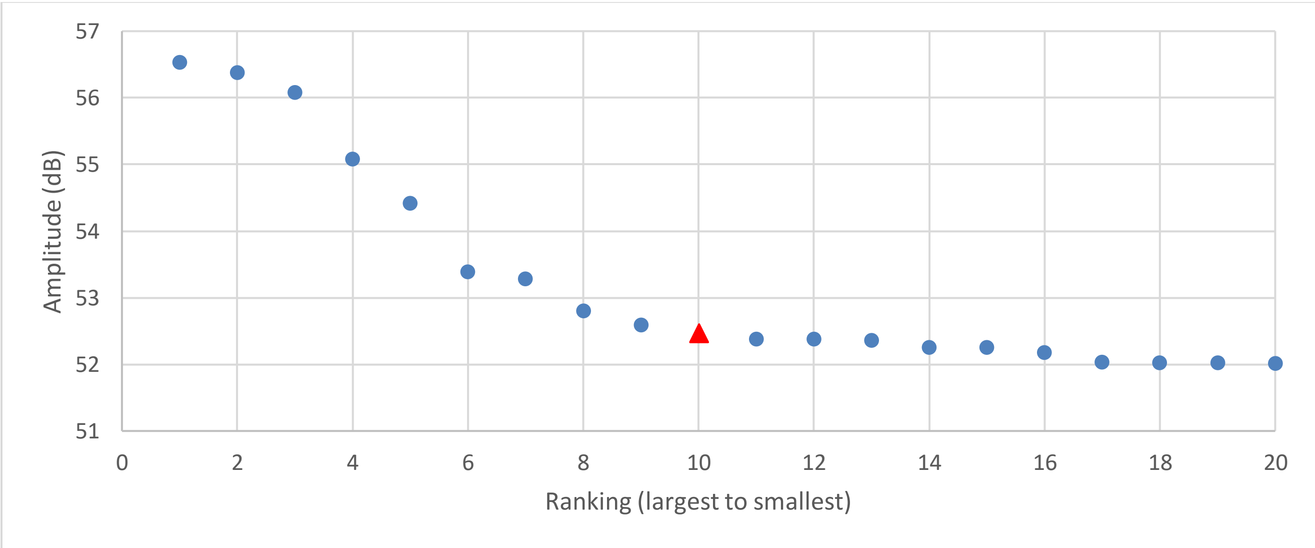

Figure 7: Structure 4, 20 Largest Data Points in the Data Set

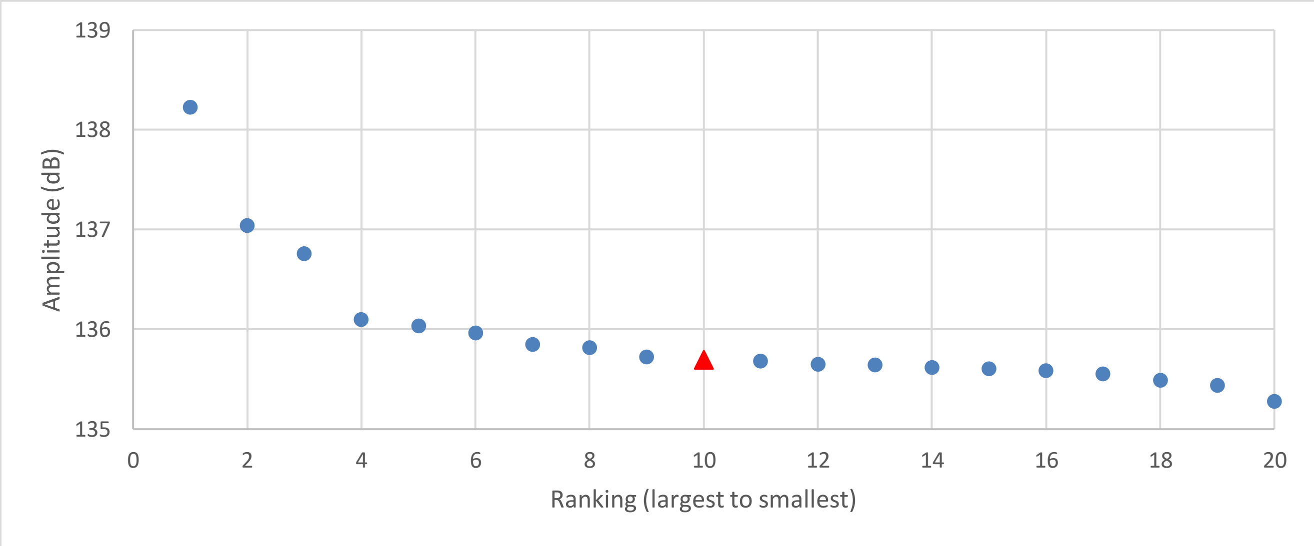

Figure 8: Data Set 5B, 20 Largest Data Points in the Data Set

MODIFIED ASTM METHODOLOGY

As discussed above, the second source of accuracy reduction within ASTM D6087 is that it does not account for the effects of signal amplitude variability from sources such as variability in the asphalt thickness, rebar cover, or reflection at the asphalt concrete interface. The variability in rebar cover and asphalt thickness affects the reflection coefficient at the asphalt concrete interface by changing the angle of incidence between scans. If the rebar cover, asphalt thickness, and reflection at the asphalt concrete interface were constant for all readings then the method outlined in ASTM D6087 should produce accurate results as the only cause of variability within the data set would be attenuation due to the chloride content. However, as was found in this study, the rebar cover, and asphalt thickness are not constant over the entire deck area. To address these inaccuracies a number of modifications to the ASTM D6087 analysis method were implemented.

The variability in reflection amplitude due to varying asphalt thickness and rebar cover was accounted for using Fresnel’s Law (EQ. 1), and Snell’s Law (EQ. 2). As the asphalt thickness and rebar cover vary the angle of incidence changes resulting in variable reflection coefficients. The method used in this work assumes the velocity of the EM pulse in the asphalt and concrete is constant over the bridge surface. The amplitude of the rebar reflection was corrected to account for variability in the reflection coefficient at the asphalt concrete interface by dividing the rebar amplitude by the refraction coefficients. Figure 9 shows the wave path with the angle of incidence and reflection noted.

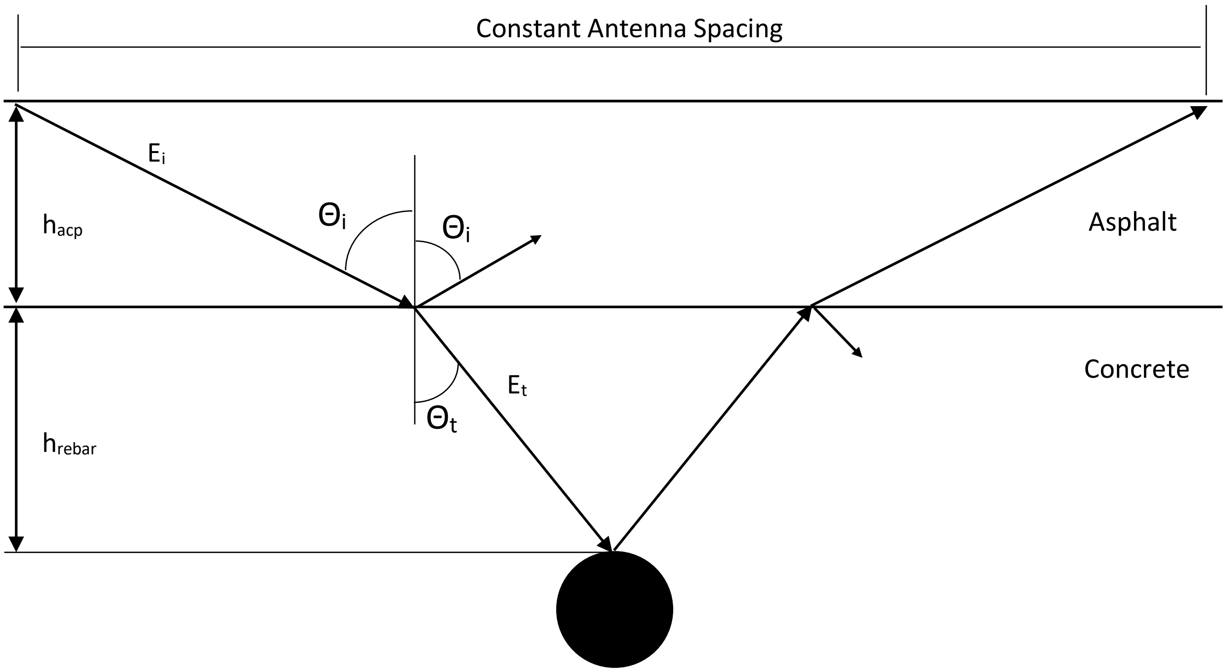

Figure 9: Wave Path with Reflection and Transmission Angles Noted

$$r = \frac{\sqrt{\varepsilon_{acp}}\cos(\theta_i) - \sqrt{\varepsilon_{concrete}}\cos(\theta_t)}{\sqrt{\varepsilon_{acp}}\cos(\theta_i) + \sqrt{\varepsilon_{concrete}}\cos(\theta_t)} \quad \textbf{EQ. 1}$$

$$\frac{\sin(\theta_t)}{\sin(\theta_i)} = \frac{v_{concrete}}{v_{acp}} = \frac{\sqrt{\varepsilon_{acp}}}{\sqrt{\varepsilon_{concrete}}} \quad \textbf{EQ. 2}$$

$r = reflection\ coefficient$

$\varepsilon_i = relative\ permittivity\ of\ material\ i\ (unitless)$

$\theta_i = angle\ of\ incidence$

$\theta_t = angle\ of\ transmission$

The variability in rebar cover and asphalt thickness also causes variability in the geometric spreading losses. Geometric spreading is the reduction in amplitude with respect to the distance travelled without a loss of energy. A textbook example would be throwing a rock in a pond. As the wave gets farther away from the impact location the height of the wave decreases as the wave energy is spread over a larger area. With respect to GPR, the amplitude of the returning EM pulse decreases as the asphalt thickness or rebar cover increases. The effects of variable rebar cover and asphalt thickness (geometric spreading) on the amplitude of the returning EM pulse was removed by normalizing the entire data set to the 90^{th} percentile of the data set (Barnes, Trottier and Forgeron 2008) (Romero, et al. 2015).

Figure 10 is an example data set for an exposed concrete deck that shows the reduction in the rebar reflection amplitude with an increase in two-way travel time (TWTT). The first step is to determine the 90^{th} percentile of the data set, see Figure 11, after which a linear best fit curve was determined so the data can be normalized for any TWTT. Finally, Figure 12 shows the normalized data for the data set. It can be seen that the rebar reflection amplitude no longer decreases with TWTT.

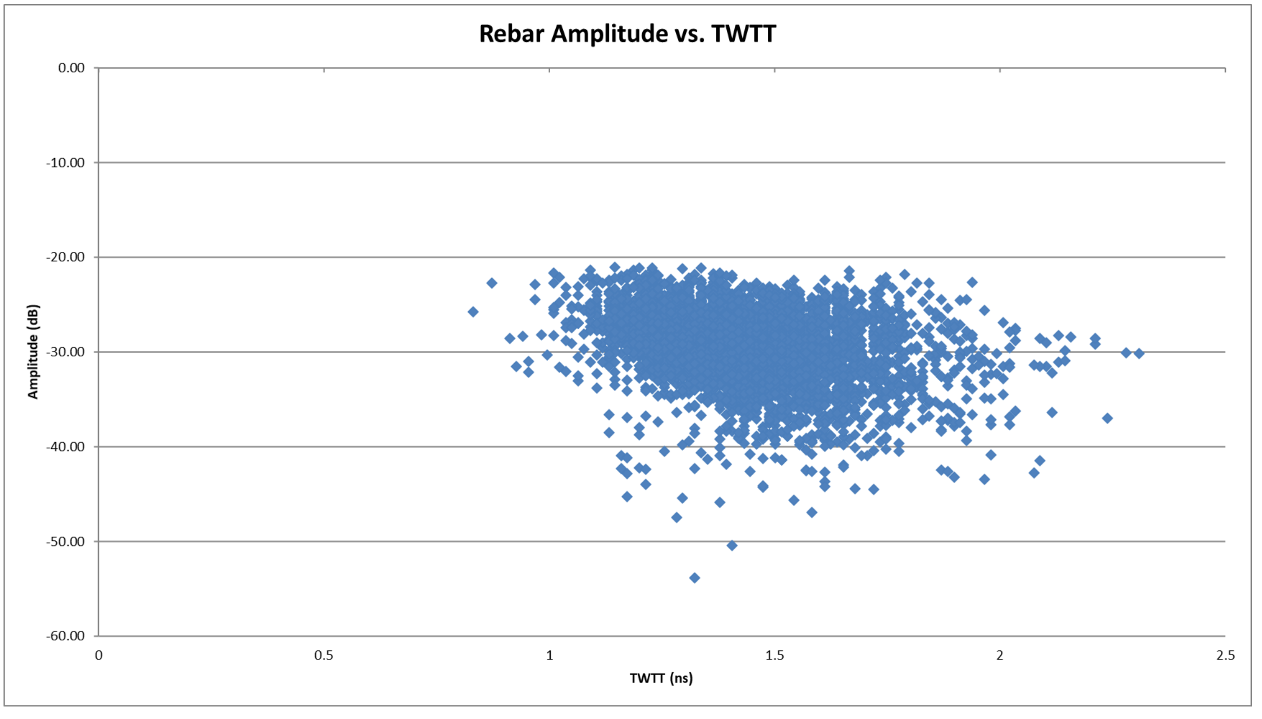

Figure 10: Raw GPR Data

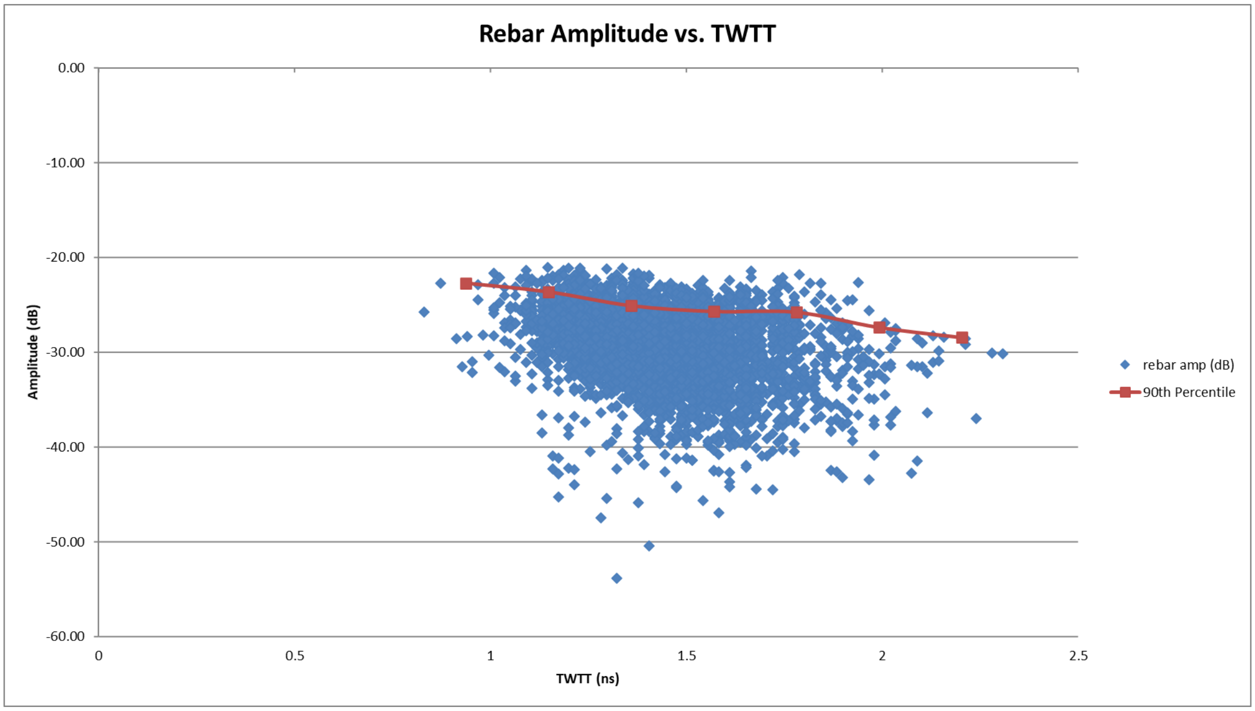

Figure 11: Rebar Amplitude and 90th Percentile Curve

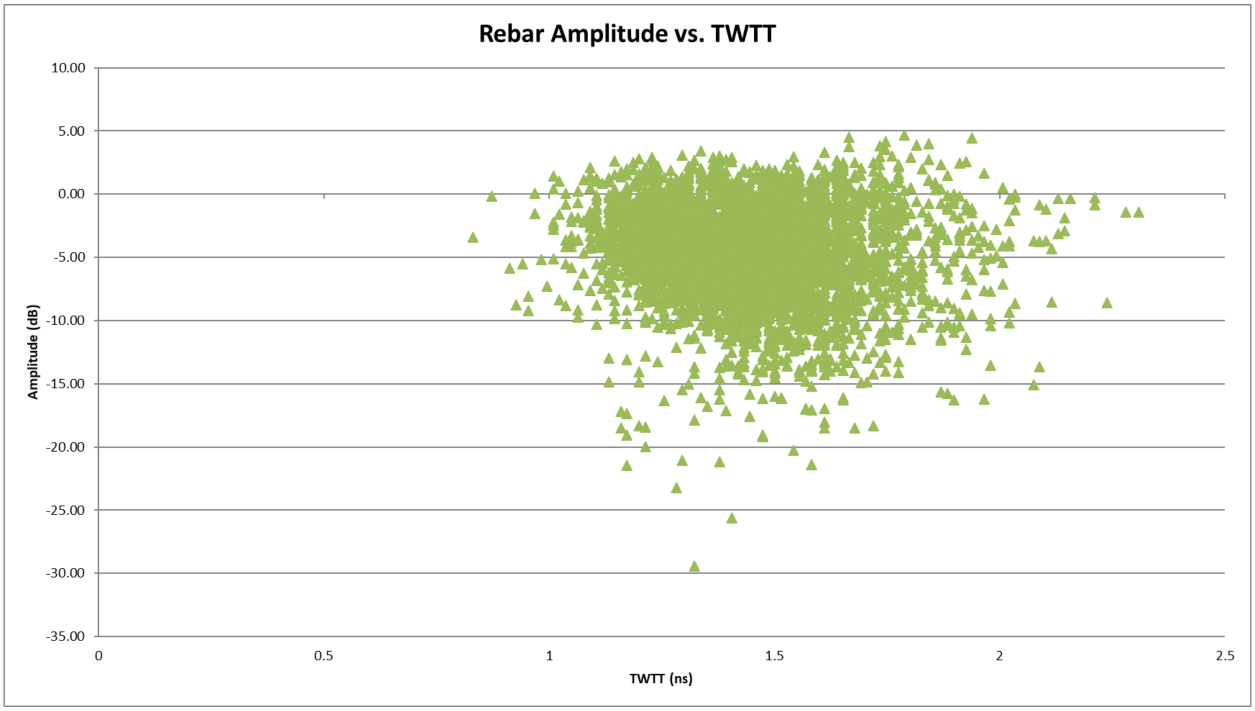

Figure 12: Normalized Rebar Amplitude Data

Once the reflection losses and geometric spreading are removed from the data set, attenuation is the only source of signal variability. Attenuation is a reduction in amplitude due to energy loss. A higher conductivity of the concrete increases the signal attenuation in concrete bridge decks. The source of high conductivity in concrete bridge decks is chloride that comes from the application of deicing salts. The premise in using GPR to detect chloride is that attenuation causes a reduction in the amplitude of the returning EM pulse; any rebar with an amplitude below a threshold value is therefore in a high chloride environment.

CHLORIDE CONTAMINATED AREA

Regardless of how the GPR data was analyzed the chloride contaminated areas were calculated following ASTM D6087, EQ. 3

$$X = \frac{(W_{dt})}{(W_{dt} + W_{st})} * 100 \qquad \textbf{EQ. 3}$$

$X = Percent\ deck\ area\ with\ high\ chlroides\ at\ or\ above\ top\ steel$

$W_{dt} = Number\ of\ reflection\ amplidutes\ indicating\ high\ chloride\ at\ or\ above\ top\ steel$

$W_{st} = Number\ of\ reflection\ amplitudes\ indicating\ low\ chloride\ at\ or\ above\ top\ steel$

RESULTS

ASTM METHODOLODGY (ADJUSTMENT TO MAXIMUM AMPLITUED)

Table 1 compares the results from the “Pure” or unaltered ASTM standard methodology with our proposed methodology, described above, that bases the threshold values on the “maximum” amplitude of the non-outlying data points. The lower and upper bounds, in Table 1, are using 8 dB and 6 dB below the “maximum” amplitude as the threshold values, respectively.

When non-outlying data is used to determine the reference point for the threshold value, the GPR results are closer to what would intuitively be expected for an 18 year old superstructure with a waterproofing membrane. For structures 3, 4, and 5 the results for the proposed methodology are still suggesting larger areas of chloride contamination than would be expected, given the age of the superstructure, but are much more reasonable than the “Pure” ASTM standard. The likely cause of these seemingly high results is that the proposed methodology still does not account for variability in asphalt thickness and rebar cover.

Table 1: Results of "Pure" ASTM and ASTM

Bridge	Pure ASTM		ASTM	
	Lower	Upper	Lower	Upper
1	20.57%	71.43%	1.62%	10.93%
2	21.36%	81.03%	0.48%	2.51%
3	24.70%	51.73%	11.06%	37.04%
4	83.62%	94.62%	34.62%	61.45%
5	39.78%	65.53%	18.35%	39.54%

MODIFIED ASTM

All five structures were tested using GPR and conventional testing methods to determine the appropriate repair strategy for each structure. This means a global understanding of the deck is more important than comparing localized results for each test. As such the result ranges and averages will be compared to get an understanding of the current condition of the bridge decks.

The testing for this structure followed the Ontario Structure Rehabilitation Manual (OSRM). Four tests were conducted:

- Ground Penetrating Radar (GPR),
- Chloride Sampling,
- Corrosion Potential,
- AC Resistance.

The corrosion threshold value for the chloride results was taken as 0.05% mass of chloride/mass of concrete. Corrosion potential results below -350 mV were taken to indicate a high probability of corrosion, and results between -200 mV and -350 mV (transition zone) were taken to indicate a moderate probability of corrosion. AC resistance results below 1.0 kΩ were taken to mean the epoxy coating was no longer providing a physical protective barrier for the rebar. The GPR lower and upper bounds, in Table 3, are using 8 dB and 6 dB below the "maximum" amplitude as the threshold values, respectively. When converting to relative probability for GPR, low is an estimated chloride contamination area of less than 10% of the total deck area, moderate is 10% to 20%, and high is an estimated contamination area greater than 20% of the total deck area.

The GPR, and chloride results, as seen in Table 2 and 3, indicate each structure has a low probability of corrosion, whereas the corrosion potential results, in Table 2, are indicating a moderate to high probability of corrosion.

The AC resistance results, in Table 2, are suggesting the epoxy coating is not providing a continuous protective barrier for the rebar on structures 2, 3, and 5 based on OSRM's criteria. Given the age of the structures (18 years), the "failed" coating is likely localized coating defects, such as cuts and punctures, that occurred during construction.

Table 2: Results of Conventional Testing Methods

Bridge	Chloride		Corrosion Potential (mV)		AC Resistance. (kΩ)	
	Range	Average	Range	Average	Range	Average
1	0.015% - 0.034%	0.023%	-162 to -507	-360	0.2-2.3	1.26
2	0.015% - 0.027%	0.021%	-294 to -405	-351	0.2-0.9	0.60
3	0.020% - 0.031%	0.025%	-244 to -477	-339	0.1-1.1	0.44
4	0.021% - 0.034%	0.028%	-306 to -451	-400	0.6-2.7	1.38
5	0.015% - 0.031%	0.021%	-243 to -600	-447	0.1-4.5	0.65

Table 3: GPR Results Comparing ASTM and Modified ASTM

Bridge	ASTM		Modified ASTM		Standard Deviation (mm)	
	Lower	Lower	Lower	Upper	Asphalt Thickness	Rebar Cover
1	1.62%	10.93%	0.15%	0.77%	15.3	12.1
2	0.48%	2.51%	0.00%	0.24%	8.7	11.0
3	11.06%	37.04%	0.39%	5.12%	7.9	8.9
4	34.62%	61.45%	2.81%	10.55%	8.6	17.6
5	18.35%	39.54%	3.91%	5.13%	10.6	14.9

The GPR results for the modified ASTM analysis match the chloride results and are closer to what would be intuitively expected given the age of the superstructure and waterproofing membrane. The corrosion potential results for all 5 structures indicate a moderate to high probability of corrosion which does not match the chloride results, GPR results, or what would be expected given the age of the superstructures. This leads to the conclusion that the corrosion potential results are not representative of the actual corrosion activity of the rebar. The exact cause of the low corrosion potential results is unknown, but possible explanations could include concrete mix, moisture content, oxygen content around the rebar, chemical treatment of the concrete, or chemical contamination. The unexplained corrosion potential results highlight the importance of doing multiple tests when trying to determine the current condition of a bridge deck.

Table 4 shows the relative probability of corrosion identified by each test and the overall probability of corrosion occurring on the structure.

Table 4: Relative Probability of Corrosion

Bridge	GPR (ASTM)	GPR (Modified ASTM)	Chloride	Corrosion Potential	Overall Probability
1	Low – Moderate	Low	Low	High	Low
2	Low	Low	Low	High	Low
3	Moderate – High	Low	Low	Moderate	Low
4	High	Low – Moderate	Low	High	Low
5	Moderate – High	Low	Low	High	Low

CONCLUSION

The ASTM D6087 method overestimated the area of chloride contaminated concrete on the test bridges. When non-outlying data points were used to determine the threshold value, versus the maximum recorded amplitude, the results became more in line with what was expected based on the age of the superstructure and chloride test results but were still high. The GPR results were further improved with a number of modifications that corrected the rebar reflection amplitude, for variability due to asphalt thickness, rebar cover, and variable reflection at the asphalt concrete interface. These modifications to ASTM D6087 produced more accurate results for the five asphalt overlaid test bridges than the method outlined in ASTM D6087, as shown through the chloride results comparison and when considering the superstructures’ age. Therefore, the method described above will provide better information to bridge owners allowing for more informed decisions and improved repair quantity estimates. This increased accuracy allows for better decision making on the timing and nature of any recommended bridge repairs, leading to improved cost savings over the lifespan of the bridge.

RECOMMENDATIONS

Further research should be done to see if the accuracy of this method can be improved. There are two considerations for future work. The impact of local site conditions on signal reflection variability at the asphalt concrete interface should be considered. Non-destructive means, such as back calculations through reflection coefficients, could also be used to determine the EM pulse velocity.

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