State-of-the-Art Bridge Deck Condition Evaluation and Management Using Ground Penetrating Radar

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Abstract

The accuracy of ground penetrating radar surveys for predicting corrosion damage in reinforced concrete decks has improved dramatically over the past 10 years. These improvements have occurred largely due to corrections for depth-related effects and the use of more complex models to represent the movement of radar signals through the concrete. GPR surveys are a valuable component in a toolbox of condition evaluation methods available to maintenance engineers. Unlike visual inspection, the method is not limited to detecting surface indicators of damage, but is instead used to non-destructively probe the interior of the deck system to locate defects and local excesses of moisture and chloride which cause signal amplitude losses. The survey results are typically used to produce a plan view map indicating the location and extent of probable corrosion damage. While GPR alone can provide highly accurate results on unpaved decks, a multimodal approach using two or more condition evaluation methods best provides a conservative estimate of corrosion damage on paved decks. The GPR results are used to reject repair candidates that are in good condition, and to prioritize others for further condition evaluation and repair. The locations delineated by GPR for both sound concrete and probable corrosion damage are used to focus addition investigation using traditional methods such as the chain drag, half-cell potential and coring surveys. The combined analysis of all results provides less variability in estimating repairs, allowing the selection of the appropriate repair method before tendering the work and providing better control on repair pricing and costs.

1. Introduction

Estimating the maintenance requirements of reinforced concrete highway decks can present a difficult challenge, particularly since the existence of corrosion largely depends on the amount of de-icing salts chlorides that may have diffused through a highly variable range of as-built concrete cover thickness. Most transportation agencies still employ mainly visual inspection methods to estimate the quantity of repairs required in a given structure, prior to tendering the work. While visual inspection can provide indications of some of the internal damage, manifested through cracking, moisture, efflorescence, and rust staining, the amount and distribution of chloride versus depth into the concrete and individual bars depths remain unobserved. As a result, corrosion damage that is of sufficient severity to produce external symptoms can included in repair estimates, but active corrosion that has not sufficiently progressed or has produced non-discernible symptoms can be overlooked. Coupled with operator subjectivity, the limited scope of visual inspection can result in a large variation in errors (1) that tend to drive maintenance costs upward in the long term. These upward trends result via cost overruns to the owner due to low repair estimates that resulted in high unit repair prices, or via unit price increases by contractors due to excessively high repair estimates that have eroded profitability.

Non-destructive evaluation methods such as Ground Penetrating Radar (GPR) provide the capacity to investigate the internal condition of such visually opaque structures in a comparatively rapid, thorough, and inexpensive manner compared to conventional investigations which can include coring, hammer or chain drag sounding (2), half-cell potential (3) and more extensive traffic control requirements. GPR is typically deployed using either a ground-coupled or an air-coupled antenna system. Air-coupled systems can be used to collect data from highway decks within traffic flow, requiring little traffic control. The speed at which the data can be collected depends on the transmission, sampling and spatial data resolutions being used. Regulatory agencies have limited transmission rates in some countries, which can limit the benefits of air-coupled systems and forces the need for increased levels of traffic control. Furthermore, given typical operating heights of 300 mm (18 inches) used for air-coupled systems, the size of the area or 'footprint' illuminated by the antenna is large compared to small regions of corrosion and damage. Conversely, ground-coupled systems, which maintain intimate contact with the deck, typically illuminate small areas, can image individual reinforcing bars, and provide high resolution maps of the deck condition. These systems generally require lane closures while recording data, typically via walking a survey cart or handheld antenna along the length of a deck, but a 100 meter long to-lane deck can be surveyed within one or two hours with contiguous surface coverage. The choice of air-coupled versus ground-coupled is often based on traffic control restrictions, but many operators prefer ground coupled systems for the higher spatial resolution than can be achieved by the ability to image single reinforcing bars.

Condition evaluation of reinforced concrete decks using GPR has evolved over time from methods that sought characteristic changes in reflection shapes (4,5), to analytical methods that considered signal losses measured via the amplitude of reinforcing bar reflections and surface reflections (6-10). It has typically been assumed that the strongest reinforcing bar reflections corresponded to the locations of concrete cover that are the least contaminated by chlorides, while progressively weaker reflections correspond to areas that are more contaminated by chloride, where corrosion has initiated, or where advanced corrosion has induced cracking. These approaches sometimes resulted in condition evaluations with poor accuracy which reduced the attractiveness of the method to many transportation agencies. More recently, corrections associated with the apparent bar depth have been applied to the relative amplitudes of reinforcing bar reflections measured using ground coupled systems on unpaved decks (11, 12). Results using this technique have been closely correlated to corrosion induced damage, typically resulting in errors that were less than one percent of the deck surface when predicting the amount of concrete cover delamination. The method generally entails empirically developing a linear regression model for the strongest observed bar reflection amplitudes (dB) versus the signal travel time (ns) observed within the population of data recorded from a deck. The linear model is used to correct the data to a common 'depth', after which a threshold amplitude value could be used to identify ranges of probable deterioration.

This paper describes a new approach for modelling the relative amplitudes of reinforcing bar amplitudes measured from ground-coupled GPR data recorded on unpaved reinforced concrete decks. A non-linear model that is based on signal attenuation and geometric dispersion is presented to describe the decrease in reinforcing bar amplitude with travel time as well as to establish threshold values for delineating ranges of probable deterioration levels.

2. Material and Methods

A simple linear ray path model is frequently used in applying GPR theory to the measurement of layer thickness in civil engineering structures. It has been common practice in the literature to assume that the media through which the radar energy propagates consists of a low loss material, implying negligible levels of conductivity that would not influence the velocity. As a result, the velocity of the radar signal is typically assumed to be solely a function of the speed of light in a vacuum, c = 299,792,458 m/s (13), and the relative dielectric constant, ε_r, as shown in Equation 1.

$$v = c/\sqrt{\varepsilon_r} \tag{1}$$

This assumption is generally valid for many construction materials, such as granular bases, Portland cement concrete, asphalt concrete, etc. in pristine condition. However, once these materials become contaminated with de-icing salts, chloride concentration and the resulting conductivity increase within the pore solution.

Layer thickness is typically computed based on the transmitter-receiver separation distance, s, the signal velocity, v, and the two-way travel time delay, □t, measured difference between arrival times of the direct wave and the reinforcing bar reflection, according to Equation 2. However, older decks which have been subjected to several years of de-icing salt application can exhibit various levels of chloride ingress, due in part to differences in the concrete batches supplied during construction and variability in placement, finishing, and cure.

$$v = \sqrt{(v\Delta t/2)^2 - (s/2)^2} \tag{2}$$

The GPR signal velocity can be estimated directly from ground-coupled GPR data recorded perpendicular to the upper transverse bars observed in typical reinforced concrete simple span decks. Hyperbolic reflections occur from these bars as the two-way travel time between the direct wave and the bar reflection decreases as the antenna approaches the bar, reaches a minimum when the midpoint between the transmitter and receiver is directly over the centre of the bar, and then decreases as the antenna moves away from the bar position. The shape of the hyperbolae depend largely on the velocity of the GPR signal through the concrete, the bar diameter and orientation, and the spatial sampling rate. Many GPR analysis programs include a migration procedure in which the signal velocity can be estimated by matching theoretical hyperbolae to the measured data by adjusting the assumed velocity. Such a migration procedure forms part of the signal processing procedure used in RADAN® for condition evaluation of ground coupled GPR deck data. The approach is subjective, requiring the user to optimize the modelled velocity by balancing the amplitude of any residual hyperbolic tails of the bar signature with the formation of new upward pointing tails, or ideally collapsing any residual tails completely such that the migrated hyperbola approximates a single point after processing. The method is typically applied against the generally stronger hyperbolic reflections in the full data set where little to no chloride ingress (and hence corrosion) is assumed to have occurred in the deck. The resulting velocity can then be further calibrated using drilled core samples, but cover thickness surveys on older decks tend to exhibit high degrees of variability due to the wide spatial range of chloride ingress that can occur over the deck surface. It has been well established that high levels of signal attenuation in the GPR data can be correlated to local qualitative excesses of chloride in the concrete that occur where corrosion has resulted in the development of cracks and other damage in the concrete. The signal loss occurs due to the increased conductivity of the pore solution, which can also result in decreased signal velocity. This causes weakened reflection amplitude and an increase in the two-way travel time for bar reflections arising from chloride contaminated concrete where delaminations typically occur. Recent approaches using a log-linear correction procedure, although shown to be very effective in correcting data for apparent depth effects, have relied mainly on the reduction in amplitude without proper consideration of the increased time delay. The following approach considers a combination of geometric spreading and conductive media in both correcting and thresholding ground coupled GPR data from reinforced concrete decks.

While a ray path model provides a simple approach for estimating layer thickness, the GPR pulse signal can be idealized as a spherically spreading electromagnetic wave originating from a point source. The signal intensity of such a wave reduces according to the inverse of the distance from the source, or the radius of the spherically spreading front, as shown in Figure 1. When measured at a large distance from the point source, the relative difference in energy losses as the wave travels a short distance will be smaller and can appear to be linear in behaviour. However, at short distances from the point source, the transmitted energy is spread over a rapidly increasing surface area, which can result in significant nonlinear relative energy losses. The energy losses due to geometric spreading must be accounted for when the three dimensional antenna field is simplified using a plane wave approximation.

Equation 3 describes the geometric spreading losses (1/x) and exponential decrease in amplitude from its original value, E_0, of a plane GPR wave with distance, x, from the point source, according to the attenuation coefficient, β.

$$E(x) = \frac{E_0}{x} e^{-\beta x} \tag{3}$$

The attenuation coefficient, β, in a can be computed as a function of the material dielectric constant, ε, conductivity, σ (S/m), and magnetic permeability, μ, as shown in Equation 4. The magnetic permeability of a given material is the product of its dimensionless relative magnetic permeability, μ_r, and the magnetic constant, $\mu_0 = 4\pi(10^{-7})$ H/m. In most non-ferrous materials, μ_r is generally assumed to be equal to unity. Similarly, the dielectric permittivity, ε, of a given material is the product of its dimensionless relative dielectric constant, ε_r, and the electric constant, $\varepsilon_0 = 1/(c^2\mu_0)$ F/m.

$$\beta = \omega\mu\sigma \Bigg/ \left(2\omega\sqrt{\varepsilon\mu} \left(\frac{1}{2} + \frac{1}{2}\sqrt{1 + \frac{\sigma^2}{\varepsilon^2\omega^2}} \right)^{1/2} \right) \tag{4}$$

The GPR signal velocity in a conductive medium is expressed according to Equation 5 (14), demonstrating that conductivity tends to decrease the velocity, compared to a non-conductive medium of the same dielectric permittivity and magnetic permeability.

$$v = \frac{c}{\sqrt{\frac{\mu_r \varepsilon_r}{2}\left(1+\sqrt{\frac{1+\sigma^2}{\omega^2\varepsilon^2}}\right)}} \tag{5}$$

The following section presents three different experimental studies to evaluate a simple combined model utilizing plane wave attenuation and geometric spreading to describe the relative losses in GPR signal amplitude. The studies examined the GPR signal losses in the simple case of a metal plate placed under layers of expanded polystyrene; a newly constructed reinforced concrete deck; and an older, in-service reinforced concrete deck exhibiting corrosion damage.

3. Results and Discussion

The first experiment consisted of measuring the GPR signal intensity from a flat metal plate placed under a built up layer of 11 mm thick expanded polystyrene sheets. One single data file was recorded using a GSSI Model 5100 antenna placed on the surface of the built up layer of polystyrene sheets as the layer thickness increased from approximately 180 to 375 mm in total thickness. The data was recorded while continuously transmitting in ‘free’ mode at a rate of 100 kHz. After collecting data for approximately 5 seconds, the recording was paused while the antenna was removed and another 11-mm sheet was added to the layer. After adding a thin lift to the built-up layer, the antenna was replaced as recording resumed. The reflection amplitude (dB) as a function of distance, and therefore the measured two-way travel time (ns) of the signal from the antenna transmitter to the reflecting surface and back to the receiver, was measured and fitted to a quadratic function with a coefficient of determination equal to 1.0, as shown in Figure 1. This quadratic relationship corresponds to an inverse relationship between amplitude expressed in voltage or amplitude units versus distance according to spherical divergence of a point source.

The second experiment consisted of a GPR survey conducted on the reinforced concrete deck of a newly constructed highway overpass in Nova Scotia. The third experiment consisted of a GPR survey of an in-service highway overpass deck, located over Highway 102 near Shubenacadie, Nova Scotia. Both decks were surveyed using a GSSI SIR-20 GPR system with a Model 5100 antenna having a centre frequency of 1500 MHz. Data was recorded at a rate of 100 scans per metre in profiles aligned along the length of the deck in the direction of traffic flow. Profiles were positioned at a transverse spacing of 50 cm with the initial profile located at a distance of 25 cm from the barrier wall along the deck edge.

The GPR data was processed using the Bridge Deterioration module within the RADAN® analysis software. The data is adjusted by correcting the time-zero position to the positive peak of the direct coupling reflection which occurs between the antenna and the deck surface. This enables the direct measurement of the two-way travel time by picking the minimum reflection time of each characteristic hyperbola that originates from each transverse reinforcing bar. A Kirchoff migration is also applied to the data in order to collapse the hyperbolic reflections to a singular point that provides a simplified representation of a rebar cross-section within the deck, making it easier and more intuitive to identify and pick these data points which are used to characterize the condition of the deck. The migration also provides an estimation of the average signal velocity in the data, enabling an estimate of each transverse reinforcing bar depth.

Conventional analysis of these reflection amplitudes assumes that the weakest reflections coincide with concrete that contains the highest chloride content, creating the most favourable conditions for reinforcement corrosion to exist. However, this assumption neglects the effects of geometric spreading and reductions in the reflection intensity with distance from the antenna.

Barnes et al. (2008) developed software that corrected the rebar reflection amplitudes for geometric spreading and depth effects using a simple linear model. This procedure resulted in deck delamination estimates that were accurate within 97-100% compared to actual quantities that were determined using the chain drag survey. However, this current research employs a non-linear model to realistically account for these effects in combination with a conductive model of the concrete layer. As shown in Figure 2, the model can be fitted to experimental data to uniquely determine the permittivity and the conductivity of the concrete. Figure 2 shows the measured variation in the rebar reflection amplitude (dB) versus the two-way travel time for the newly constructed reinforced concrete deck. The non-linear model was fitted to the average amplitude values at different two-way travel times to provide a unique estimation of the average relative dielectric permittivity and the conductivity, equal to 11.15 and 9 mS/m, respectively. The permittivity appears slightly elevated compared to older in-service decks that are not deteriorated, which may typically range from values of 6 to 9. However, as a newly constructed concrete that is 2-3 months of age, it may be expected that the moisture levels and ionic content of the pore solution is relatively high. Over time as the concrete cures and matures, it is expected that the relative dielectric permittivity and the conductivity will both decrease, until exposure to chloride begins, after which the conductivity will increase with chloride diffusion. Some higher amplitude data points are observed in Figure 2 above the bulk of the measured population of rebar amplitudes. These data are measured from larger bars extending from the barrier walls out into the deck. The amplitude range of the bulk of the deck reinforcement within any given two-way travel time tends to vary over approximately 8 to 9 dB, illustrating a fairly low level of variability that might be due to subtle changes in the concrete porosity, moisture content, the orientation of deformations along the bars, and the subtle misalignment of data with the true centre of each bar.

For condition evaluation purposes in older decks, it might be assumed that the permittivity of the concrete does not significantly change until increases in the internal moisture content will occur at depth within the cover layer. These increases typically result through increases in porosity through the effects of freezing and thawing, corrosion cracking, or other deterioration processes that affect the microstructure of the concrete. Therefore, increases in signal attenuation may be assumed to be solely due to increases in conductivity arising from the diffusion of chloride. It follows that certain levels of attenuation can then be associated with the initiation of corrosion and the onset of corrosion induced cracking. Figure 3 shows the measured variation in the rebar reflection amplitude (dB) versus the two-way travel time for the Shubenacadie Hwy 102 Overpass. When compared to the distribution of rebar amplitudes shown in Figure 2, it is apparent that the older in-service deck exhibits a wider and increasing range of amplitudes for a given two-way travel time and exhibits generally higher levels of signal loss. Three non-linear models of the rebar amplitude versus two-way travel time are superimposed on the data, and differ only by the fitted conductivity parameter. The model that was fitted to the strongest reflections along the top of the data closely follows the curvature of the measured data and provides a solution of the relative dielectric permittivity = 7.43 and conductivity = 5.5 mS/m for the regions of the deck containing the least chloride content. It is interesting to note that, as expected, the relative dielectric permittivity, which is most affected by moisture content, is lower for these regions of the older deck than the newly constructed deck, while the conductivity is lower. The other two models represent a midrange and the highest conductivity values observed in the data, which can be interpreted as increasing chloride content within the deck cover layer. In reality, it is likely that the weaker reflections will also correspond to higher permittivity and conductivity values than assumed due to cracking and possible increases in porosity by other forms of deterioration.

Figure 4a shows the location and extent of chain-drag based delaminations (2), delineated in semi-transparent grey, superimposed over the distribution of GPR signal attenuation in plan view over the Shubenacadie deck surface. Note that chain drag was not conducted nor were delaminations delineated within the interior or abutment joints of the deck, while the GPR detected significant signal loss and therefore chloride ingress at these locations. The GPR results are colored in "hot" colors, ranging from yellow to red, above a proprietary conductivity threshold that corresponds to the existence of the delaminations. Less attenuated GPR data are coloured in light to dark blue shades to highlight the regions ranging from low chloride content to incipient cracking. Figure 4b similarly shows the location and extent of active corrosion as identified using the half-cell potential survey (3), delineated in semi-transparent grey, also superimposed over the distribution of GPR signal attenuation in plan view over the deck surface. Half-cell survey data were measured at one metre intervals along the length of the deck and at 0.5 metre intervals along the width of the deck. Differences in the GPR colour shading are also based on a different proprietary conductivity threshold that is representative of 90% probability of active corrosion corresponding to -0.350 V CSE (3). Figures 4a and 4b that a very high level of spatial correlation between the GPR based predictions of corrosion and corrosion induced delaminations and those which were actually found using well-established methods. While the chain drag and half-cell surveys are also subject to misinterpretations and measurement errors (1), it may also be observed that the level of apparently random false positive or false negative predictions which have often been typical in results from previous methods are relatively scarce. In fact, the GPR results can be used to locate regions of suspect corrosion activity that neither of the conventional methods were able to identify. The regions of predicted delaminations and active corrosion that can be formulated from the non-linear modelling analysis of the GPR data can be used to identify and delineate specific repair areas and quantities with a high level of accuracy.

GPR surveys can provide a high resolution condition evaluation of reinforced concrete decks. The survey results are highly sensitive to the accumulation of moisture and chloride in the deck system above the measured reinforcing bars. These results are readily integrated with conventional visual inspection approaches such as the Ontario Structural Inspection Manual (OSIM) that are broadly utilized by most transportation agencies. The benefits provided by the GPR survey results include rapid data collection and minimization of lane closures, spatial referencing of the measured data for ready transferability to drawings and GIS databases, objective analysis methods which minimize errors due to user subjectivity, and most importantly, the ability to focus other inspection methods which are used in the development of detailed condition evaluations. The identification and delineation of regions from the GPR survey where corrosion is likely to exist as a result of increased chloride content, can be used to strategically position coring, asphalt removal, chain drag, half-cell potential and other conventional survey methods that are currently relied upon to provide increased reliability in selecting repair strategies and in estimating repair quantities. The utilization of GPR surveys further increases this level of reliability by focusing where to direct these efforts with greatest effectiveness and by increasing the amount of correlating survey data to improve confidence in the results.

4. Conclusions

Ground Penetrating Radar has evolved to become a reliable, accurate and more commonplace non-destructive method for evaluating the location and extent of probable corrosion and corrosion induced damage that results from the ingress of de-icing salts through reinforced concrete decks. This evolution has resulted from several correction approaches that have been developed to address signal loss effects arising from geometric spreading and distance of reflectors from the GPR antenna. A non-linear model which also accounts for variations in the relative dielectric permittivity and the conductivity of the reinforced concrete deck was demonstrated on a newly constructed reinforced concrete deck and an older in-service deck exhibiting corrosion damage. The non-linear model was fitted to the GPR data obtained formt he new deck and identified slightly elevated permittivity and conductivity values that were attributed to unhydrated moisture and ionic pore water content in the relative young concrete. The non-linear model provided spatially and quantitatively accurate estimates of the location and extent of the corrosion damage identified on the older deck, and identified additional locations where damage was either missed by these survey methods or where higher levels of chloride may reside in the deck.

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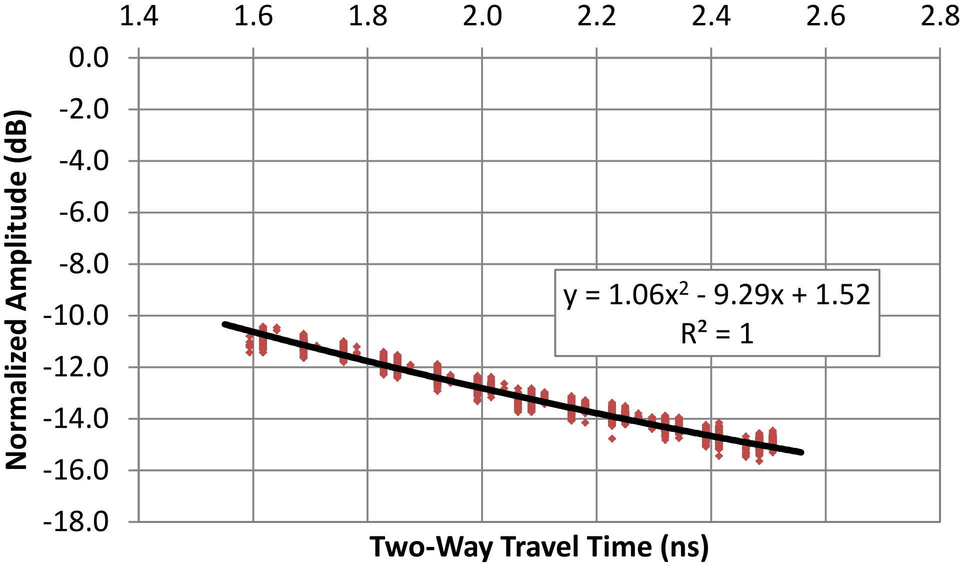

Figure 1 – Effects of geometric spreading and distance from antenna on measured reflection amplitude.

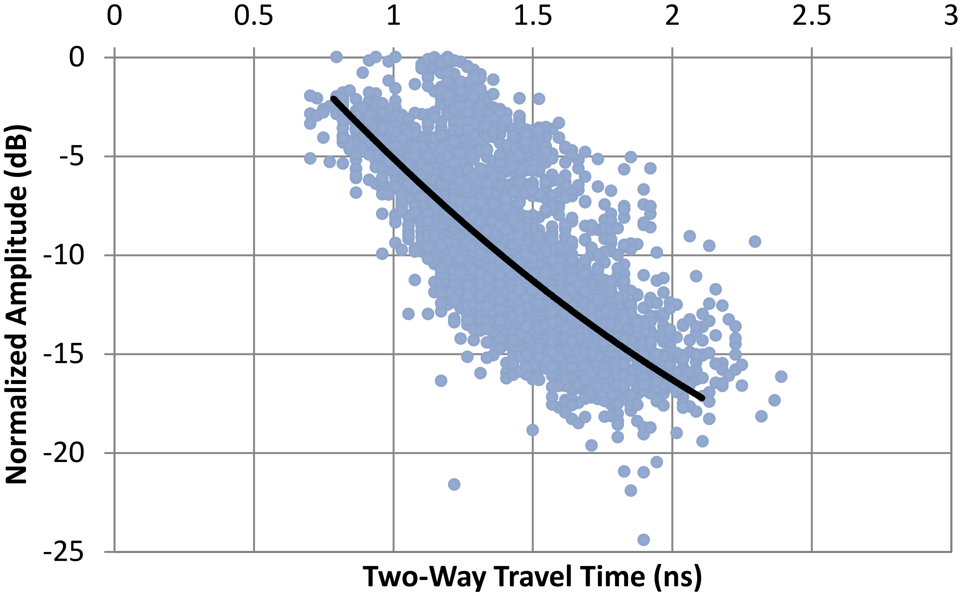

Figure 2 – Non-linear model fitted to rebar amplitudes measured from a newly constructed reinforced concrete deck.

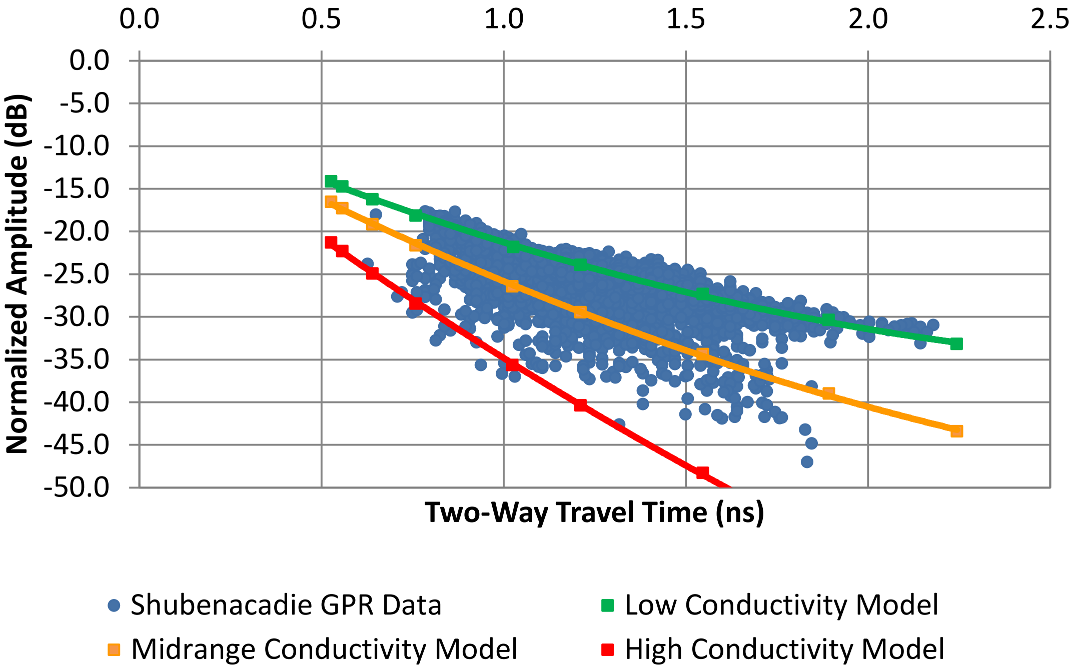

Figure 3 – Non-linear models fitted to older in-service reinforced concrete deck.

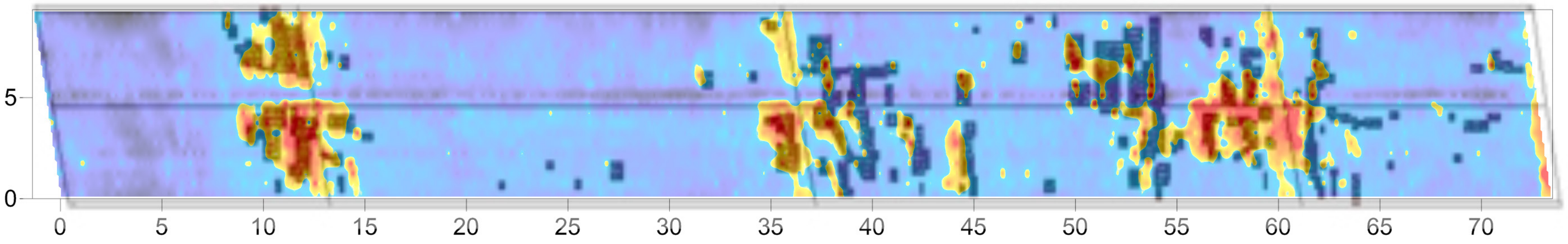

Figure 4a – Comparison between chain drag survey of deck delaminations (grey) versus non-linear delamination threshold applied to GPR survey results (yellow-red).

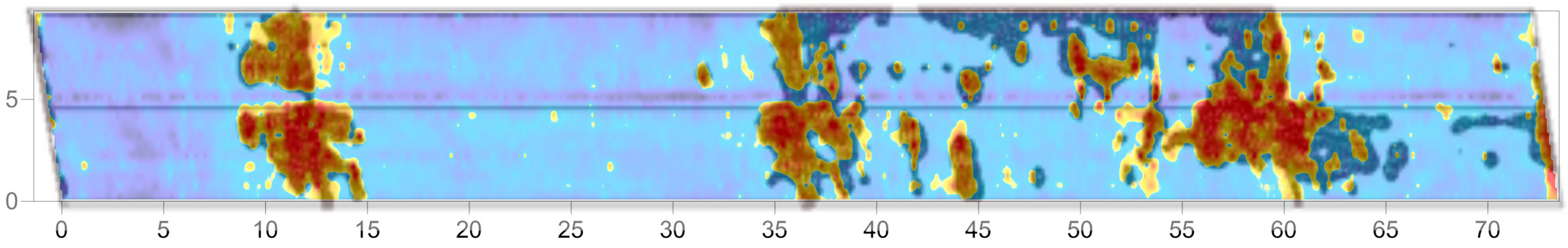

Figure 4b – Comparison between half-cell potential survey of active corrosion (grey) versus non-linear corrosion threshold applied to GPR survey results (yellow-red).