IDEA

Innovations Deserving
Exploratory Analysis Programs

NCHRP IDEA Program

Establishing NDE Protocols for Use in Early Age Bridge Deck Preservation Strategies

Final Report for
NCHRP IDEA Project 243

Prepared by:
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May 2024

NATIONAL ACADEMIES Sciences Engineering Medicine

TRB TRANSPORTATION RESEARCH BOARD

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NCHRP IDEA Program Final Report

IDEA Project NCHRP-243

Prepared for

The NCHRP IDEA Program
Transportation Research Board
National Academies of Sciences, Engineering, and Medicine

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Amir Rezvani

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5/30/2024

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ACKNOWLEDGEMENT

The project team would like to acknowledge the contributions of the members of the Infratek team, specifically Xiao Meng, Syed Zain and Ebi Maher.

The project team would like to acknowledge the contributions of the Expert Advisory Panel members, Emily Parkany, Bruce Johnson, Gregg Freeman, James Lacroix, Jason Arndt, Joseph Stanisz and Philip Meinel.

We would also like to acknowledge the contribution of GSSI Inc.'s personnel to this project who provided invaluable thoughts and ideas in the data acquisition and processing domains. We would like to specifically thank David Cist, Jacob Ferrell and Jon Algeo.

Also, we would like to acknowledge the assistance and guidance by the TRB and the National Academy of the Sciences, Engineering, and Medicine representative, Mr. Inam Jawed, as without his constant help and support this project would not have become a reality. Finally, this work would not have been possible without the support and funding from the NCHRP IDEA Program.

Glossary

NDE: Non-Destructive Evaluation

GPR: Ground Penetrating Radar

FHWA: Federal Highway Administration

DOT: Department of Transportation

DAQ: Data Acquisition

AI: Artificial Intelligence

ML: Machine Learning

EXECUTIVE SUMMARY

The research project "Establishing NDE Protocols for Use in Early Age Bridge Deck Preservation Strategies" aims to develop protocols for early age bridge deck preservation using Non-Destructive Evaluation (NDE) methods, namely High-Resolution Surface Imaging, Hairline Crack Mapping and Ground Penetrating Radar (GPR) Surveys. The data collected is processed using both conventional and AI-based techniques to create vulnerability maps, which identify areas with a higher likelihood of moisture ingress and higher crack density to provide metrics for early-age bridge deck preservation activities.

Human inspectors often overlook early deterioration triggers during the initial years of a bridge's lifecycle, leading to unnoticed deterioration. This can happen for mainly two reasons:

1. Lack of required tools to identify and quantify such triggers (e.g., hairline cracks can not be seen with the naked eye from a certain distance).
2. Human bias and subjectivity cause overlooking of deficiency in new elements/structures.

The Federal Highway Administration (FHWA) promotes a balanced approach to bridge preservation, rehabilitation, or replacement, with bridge owners seeking more strategic measures as part of overall asset management. Current inspection methods lack the capacity to recognize the need for timely preservation, resulting in delayed actions and reduced benefits. This research challenges the status quo by providing asset owners with accurate and timely metrics to make effective decisions to preserve their bridge decks. As a result, only practical and field-deployable methods and practices were examined, tested, and evaluated during the course of this research to ensure the results are not just theories that can be achieved in the laboratory environment but are practical methods that can be easily implemented in the field by asset owners with no disruption to traffic.

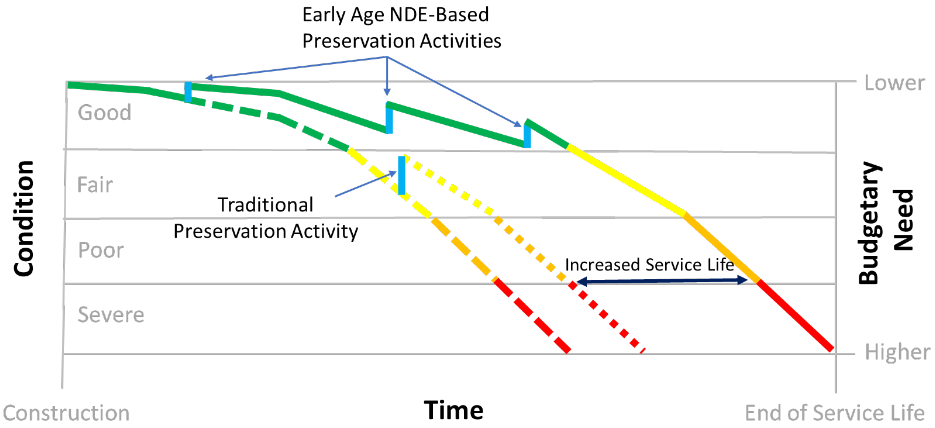


Figure 1- Benefits of timely bridge preservation

To demonstrate the feasibility of the proposed innovation, the project achieved several critical outcomes. These include conducting laboratory and field testing to assess whether it is practical and possible to quantify the depth and rate of water penetration into the concrete using customary GPR equipment and data processing methods. High-resolution surface imaging at high speed plus crack mapping of bridge decks was also performed to quantify crack width for cracks as small as 0.004” along with distribution/density. To meet the field-applicability criterion of this research these methods shall be capable of being deployed at traffic speed to eliminate the need for lane closure and not cause any traffic disruption.

Data processing and fusion techniques were then used to establish a correlation between crack density and moisture retention amount resulting in an in-situ condition state of the deck termed the vulnerability index. The vulnerability indices were then further processed to form color coded plots and these vulnerability contour maps for surveyed in-service bridge decks were produced as part of the final stages of the work. The results are documented and associated with the most suitable preservation techniques for any given index.

The project team dedicated significant time to refining the research hypothesis and conducted a comprehensive requirements analysis that shaped the features of the Vulnerability Detection function. Multiple meetings with industry and NDE equipment partners have fine-tuned data acquisition and processing algorithms. Laboratory tests on time-lapse GPR assessed the feasibility of identifying the rate of moisture ingress and retention metrics in concrete. Initial findings indicated the need to adjust methods, leading to the development of a new approach considering overall moisture retention as a factor in calculating the vulnerability index.

To ensure field applicability and usability, state DOTs participate in every stage of the work. Vermont Agency of Transportation, Iowa DOT, Wisconsin DOT, Delaware DOT, Indiana DOT and Texas DOT have provided feedback on useful information for the early preservation of bridge decks. As the main goal of this study was to produce well-rounded, field-applicable methods, the project team made field data collection from in-service bridges a cornerstone of this project. As a result, by partnering and cooperating with several state DOTs (Iowa DOT, DelDOT, Indiana DOT, and Texas DOT), the project team managed to collect a good amount of data from recently constructed bridge decks in Iowa, Indiana, Texas, and Delaware to process and assess for detection of vulnerable areas, calculate the vulnerability index and produce the vulnerability contour plot. The application of the methods developed in the stage of this work on the collected data sets resulted in the following results:

- Bridge decks, no matter how new, start cracking within days after construction and curing of the concrete. This is well validated by the literature, field observations and the extent of cracking the processed data showed on this project’s data sets.
- Taking images with enough pixel resolution to enable the detection of surface cracks as small as 0.004 in. wide was a major breakthrough that took place during this project.
- The Trained Artificial Intelligence (AI) algorithm is now capable of finding cracks as small as 0.004 in. on new decks.
- Transitioning the surface crack maps into density plots (including the hairline cracks) can unlock invaluable insight into which areas of the new deck may require early maintenance to block the intrusion of moisture and chlorides at such an early age.
- Areas of the bridge deck that have higher moisture content tend to show higher dielectric constant calculated by the GPR system as a result of higher signal attenuation compared to other areas of the deck.
- Combining the surface crack density data and the dielectric density data results in an index value that is indicative of surface condition (density of cracking) and moisture retention (higher dielectric than the baseline value for higher moisture) and thus can be used to quantify the amount of vulnerability.

As part of the transfer-to-practice efforts of this project, the field data collection methods, data processing, and analysis techniques will be presented at various regional and national bridge preservation partnership conferences as well as monthly calls. The project team has also submitted an abstract of the work that is selected by the review committee to be presented at this year’s National Bridge Preservation Partnership Conference in South Lake City, UT, in September 2024. The vulnerability plots, as well as the index, can be utilized by the bridge owners as an objective metric in prioritizing the newer decks in their inventory for preservation activities where a higher vulnerability index shows a higher likelihood of onset of corrosive activities due to higher ionic conductivity which can increase the risk of corrosion in steel reinforcement.

IDEA PRODUCT

The product of this IDEA project is a method to calculate a vulnerability index for a given bridge deck as well as units of surface area on the said bridge deck with the following considerations:

1. This method takes into account the crack density of each unit of surface area.
2. It takes into account the increased dielectric constant of the unit of surface area versus the background or the same number under wet conditions (whichever is available).
3. The cracks within the unit of surface area can be as small as 0.004 in. to be included in the calculations.
4. The data collection method can image the deck's surface at 55 mph, producing images with sufficient resolution to show cracks as small as 0.004 in. wide.
5. The image processing technique is based on Machine Learning (ML) and is trained to detect concrete cracks as small as 0.004 in. wide.
6. The image processing technique can ingest 5 different ranges set by the user for crack classification purposes.

This Method has two main outputs that can be used by bridge owners to move towards objective data-driven decision-making for their bridge preservation programs:

1. A vulnerability Index Associated with the Entire Bridge Deck: This number can be used as an objective data-driven factor in decision-making to compare and prioritize candidate bridges in upcoming preservation programs.
2. A vulnerability plot: This plot indicates the more vulnerable locations of the bridge deck to corrosion by identifying the areas that have stronger facilitators (surface cracks and moisture).

According to the Federal Highway Administration (FHWA), effective bridge preservation can reduce maintenance costs by up to 50% by addressing minor issues early, preventing them from escalating into costly major repairs or replacements. Our method not only identifies early issues that are hidden from the naked eye but also introduces objective methods for quantifying and prioritizing these issues, ensuring that the more severe problems are addressed promptly.

CONCEPT AND INNOVATION

A bridge deck serves as the protective layer of the structure. However, the ingress of moisture and early age cracking in a steel-reinforced concrete bridge deck are often overlooked in their relationship to the overall trajectory of its deterioration. As Cody (1994) states, "Water, penetrating through these cracks, is the most important substance that is involved in virtually every form of concrete deterioration-freezing-thawing damage, reinforcement corrosion, alkali-aggregate reactions, dissolution, sulfate attack, and carbonation."

Existing methods for bridge inspection fail to effectively detect early-age deterioration within the deck. Moisture ingress, along with chlorides and other harmful substances, initiates further cracking and corrosion of the steel reinforcement, often going unnoticed for several years. This delay in detection and action can be attributed to several factors:

1. Inadequate Visual Inspections: The primary method for evaluating bridge deck condition has been visual inspection, which is insufficient to identify early signs of vulnerability for many reasons with a few of them as follows:

    a. Early-age cracks are often very small in width (hairline) and are concealed from the naked eyes of the inspectors.
    b. Capturing the full extent of cracking by human inspectors on a large area is a major undertaking. As a result, the inspectors often only log the areas showing wide cracks.

2. Lack of Advanced Tools: Precise, repeatable tools that provide high-quality, accurate data for detecting early age deterioration have yet to be commercially available.

3. Manual Data Collection: Traditional methods for acquiring detailed data are manual, time-consuming, and costly, requiring extended traffic lane closures that are impractical for agencies and inconvenient for the public.

4. Insufficient Data Processing: Raw data alone is inadequate. Commercial-grade data processing and fusion techniques that convert various data sets into actionable insights about early age deterioration do not exist.

5. Limited Industrial Approaches: Due to the lack of industrial methods for detecting early age deterioration using NDE, such activities are carried out manually by highly experienced research institutes in an ad hoc manner. This demands significant labor and causes extended traffic lane closures, thus limiting adoption.

A major barrier to effective early-age preservation has been the lack of efficient data collection technologies as well as data processing techniques that can detect and quantify the factors involved. Infratek has addressed this issue by developing and deploying a high-speed data acquisition (DAQ) vehicle capable of collecting all necessary data types at highway speeds with the required resolution and accuracy. This DAQ system and its derivatives have enabled new research opportunities previously not feasible. The current research leveraged the data sets that were acquired from in-service bridges by this system. Unique data processing and analysis techniques were also developed to ensure the results generated from this research are accurate and repeatable.

The challenges outlined above necessitate an innovative solution tailored to the environmental and unique characteristics of each bridge under investigation. Differences between bridges, national weather zones, and varying preservation approaches by bridge owner organizations (e.g., state DOTs, toll authorities) demand a customizable and adaptable strategy.

Our proposed innovation leverages data collected from two advanced NDE methods: Ground Penetrating Radar (GPR), and High-Resolution Surface Imaging combined with AI Crack Mapping. Infratek has extensive experience using these methods to assess bridge deck conditions. However, this project focuses on a novel way of fusing the resulting data of these data acquisition (DAQ) methods and AI-based data processing and fusion techniques. Our comprehensive literature review and interviews with bridge owners have revealed that these methodologies have not been previously implemented to identify bridge preservation triggers, especially when the bridge decks are brand new. The innovative deployment has shown significant promise in theoretical and lab tests conducted at Infratek.

The innovative application of these technologies is described below:

1. Ground Penetrating Radar (GPR): Typically, GPR surveys are point-in-time tests used to assess the concrete structure for moisture ingress and determine the cover depth of the top reinforcement steel mat. For this research, Infratek proposed to assess conducting GPR surveys in a "time-lapse" fashion with high repeatability to study water ingress rates. This involved spraying laboratory specimens with a known amount of water and conducting time-lapse GPR surveys by scanning and re-scanning the same specimen over a specific period (e.g., every 2 hours for 24 hours). This method, while valuable for theoretical research, proved too complex for practical field application due to the need for repeated data collection over extended periods on the bridge. As a result, it was not pursued for field deployment. Instead, in collaboration with GSSI, the project team investigated using the dielectric constant estimated by the air-launched GPR apparatus. This approach showed significant promise in both lab and field tests and has been selected as the final method for the model.

2. Surface Imaging and Automated Crack Mapping: Cracks are a critical factor in bridge deck deterioration, as they facilitate water and chloride ingress, leading to reinforcement steel corrosion and concrete deterioration. Infratek utilized a customized surface imaging and crack mapping system that was built in-house, which was further refined for the high-resolution requirements of this research. High-resolution images were captured while traveling on the bridge at speeds of 55 MPH, detecting hairline cracks as small as 0.004 in. using a custom-developed artificial intelligence-based crack mapping system tailored for this project.

3. Data Fusion: The GPR and crack mapping data sets were processed using both conventional and AI-based algorithms to generate vulnerability maps. These maps are based on moisture retention/content of the deck for any unit of surface area and the density of hairline and other cracks on the same unit of surface.

Through these innovative methods, we have successfully implemented a unique approach from data collection to data processing, fusion, and production of invaluable insight in the form of metrics and plots for early-age bridge deck preservation, providing accurate and timely metrics for asset owners to utilize to make more effective preservation decisions.

INVESTIGATION

Our investigative approach includes several tasks integrated within two main stages to demonstrate the proposed method's technical merit and field applicability. These objectives, along with their associated technical tasks, success metrics, and alternative strategies for each objective, are explained below.

	Month																	
Stages and Tasks	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Stage 1. Protocol Development, Laboratory and Field Data Collection																		
Task 1. Kick off Meeting	■																	
Task 2. NDE Protocol and Hypothesis Development and Analytics Studies	■	■	■	■														
Task 3. Data Collection Strategy, Sample Selection, Data Collection and Validation	■	■	■	■	■	■	■	■	■	■								
Task 4. Data Processing, Algorithm Development, Training and Testing					■	■	■	■	■	■								
Task 5. Stage 1 Report and Project Progress Review										■								
Stage 2. Outcome Analysis and Preservation Activity Recommendation																		
Task 6. Outcome Analysis, Further Validation, NDE Protocol Finetuning											■	■	■	■	■			
Task 7. Preservation Activity Identification, Correlation and Analysis Based on the Outcomes												■	■	■	■			
Task 8. Final Report																■	■	■

Figure 2 - Project Plan

STAGE 1. PROTOCOL DEVELOPMENT, LABORATORY, AND FIELD DATA COLLECTION

During this stage of the project team developed the general research hypothesis that is the building block of this entire endeavor to determine protocols that correlate aggregate characteristics of surface cracking (such as density) with the expected permeability of a bridge deck (using moisture retention as a factor) in objective, data-driven manners. The objective is to calculate a "Vulnerability Index" based on a mathematical relationship between the extent of cracking (measured by crack length and width) and the anticipated permeability of the deck (measured by the GPR survey's dielectric constant calculations).To further explain this relationship and why each element is important, we will look at why the measurement of each factor is important for recently constructed bridge decks:

Surface Cracking – Hairline and More

Early age cracking in newly constructed concrete bridge decks has become a common and significant issue that can compromise the structure's long-term durability and performance. These cracks typically appear within the first few days to weeks after concrete placement and can result from various factors, including thermal stresses, shrinkage, and mechanical loading.

- Shrinkage: Shrinkage is another critical factor. There are two main types of shrinkage: plastic shrinkage and drying shrinkage. Plastic shrinkage occurs when the surface of the concrete loses moisture faster than it can be replaced from below, usually within the first few hours after placement. Drying shrinkage happens over a longer period as the concrete loses water to the environment. Both types of shrinkage can cause the concrete to contract and crack if the tensile stresses induced are greater than the concrete’s capacity to withstand them.
- Mechanical Loading: Premature loading, whether from construction activities or traffic, can also induce early-age cracking. Newly placed concrete is particularly vulnerable to cracking if it is subjected to significant loads before it has achieved sufficient strength.
- Thermal Stresses: One of the primary causes of early-age cracking is thermal stress. As the concrete hydrates, it generates heat. The temperature rise can lead to thermal expansion, and subsequently, as the concrete cools, it contracts. If the temperature differential between the surface and the interior of the concrete is significant, it can induce tensile stresses that exceed the material's early-age tensile strength, leading to cracking. It shall be noted that, on bridge decks shrinkage cracks are more expected than thermal as bridge decks are not very thick and have a large surface area, limiting the temperature rise from hydration.

Importance of Early Detection and Action

Early detection and mitigation of these cracks are crucial for several reasons:

1. Firstly, early-age cracks can provide pathways for water and aggressive agents, such as chlorides, to penetrate the concrete. This intrusion can accelerate the deterioration of the concrete and the corrosion of steel reinforcement, leading to a reduction in the bridge deck's service life and increased maintenance costs.
2. Secondly, addressing cracks at an early stage can prevent them from widening and propagating, which would make repairs more complex and costly.

Early intervention can involve simple and cost-effective measures such as surface treatments, sealants, or minor repairs, whereas delayed action might necessitate more extensive and expensive repairs, including partial or full-depth repairs. Please note that the cracks that we are discussing at this point are mainly in the range of hairline narrow cracks which could be as small as 0.004 in. (~0.1mm) wide and barely visible to the naked eye. For comparison purposes, the size of human hair strands can be anywhere from 0.04mm to 0.12mm.

Contrary to the common perception, hairline cracks can enable the ingress of moisture, as stated in the FHWA publication by Clemena, G. G., & Virmani, Y. P. (2004). "Corrosion Protection - Concrete Bridges", hairline cracks, though narrow, are sufficient to allow moisture and chlorides to penetrate, leading to the corrosion of steel reinforcement. This document emphasizes the importance of addressing these cracks to prolong the lifespan of the bridge decks.

Moisture Retention in Concrete and Dielectric Constant

The dielectric constant of newly constructed concrete bridge decks is a critical parameter in assessing their quality and durability. This constant, which measures the ability of the concrete to store electrical energy in an electric field, is influenced by the material's composition, density, and moisture content. A higher dielectric constant typically indicates higher moisture content, which can be a precursor to potential deterioration mechanisms such as freeze-thaw cycles, alkali-silica reactions, and corrosion of reinforcing steel.

The dielectric properties of concrete, specifically the dielectric constant, can significantly change after exposure to water. This change is primarily due to the interaction between the concrete's porous structure and the water, which affects the material's electrical properties. Since concrete is a heterogeneous material composed of cement, aggregates, and pores, its dielectric properties, including the dielectric constant (relative permittivity), are influenced by the moisture content within its pores. The dielectric constant of dry concrete typically ranges from 4 to 12, depending on its composition and density.

Monitoring the dielectric constant allows for early detection of moisture ingress and other issues that can compromise the structural integrity of the bridge deck. Advanced nondestructive testing methods, such as Ground Penetrating Radar (GPR), can measure this property and provide valuable data for maintenance and preservation strategies. By understanding and controlling the dielectric constant, state DOTs and other bridge owners can enhance the lifespan and safety of concrete bridge decks, ensuring they remain resilient against environmental stressors and mechanical wear.

As a result, monitoring hairline surface cracks and the dielectric constant for newly constructed bridge decks is of paramount importance. Early detection of hairline cracks, which can facilitate the ingress of water and chlorides, is crucial in preventing the accelerated corrosion of reinforcement steel and subsequent concrete deterioration. Utilizing advanced techniques like high-resolution surface imaging and automated crack mapping enables the precise identification and quantification of these cracks, ensuring timely and effective preservation measures. Similarly, monitoring the dielectric constant through air-launched GPR provides valuable insights into the moisture content and overall condition of the bridge deck. This method allows for the early identification of vulnerabilities that might otherwise go unnoticed. Together, these approaches offer a comprehensive strategy for maintaining the structural integrity and extending the service life of bridge decks, ultimately leading to significant cost savings and enhanced safety for transportation infrastructure.

Lab Testing Setup

To ensure this endeavor stays as field-applicable as possible, the project team conducted lab experiments to ensure the proposed hypothesis and data collection methods could be successfully implemented in lab settings before moving the work to in-service bridges. In doing so, the project team utilized portable concrete blocks with varying thicknesses from 6” to 10” in its facility to conduct moisture ingress and retention tests using GPR’s dielectric data.

The figures below show the process of building the blocks as well as the setup of the test.

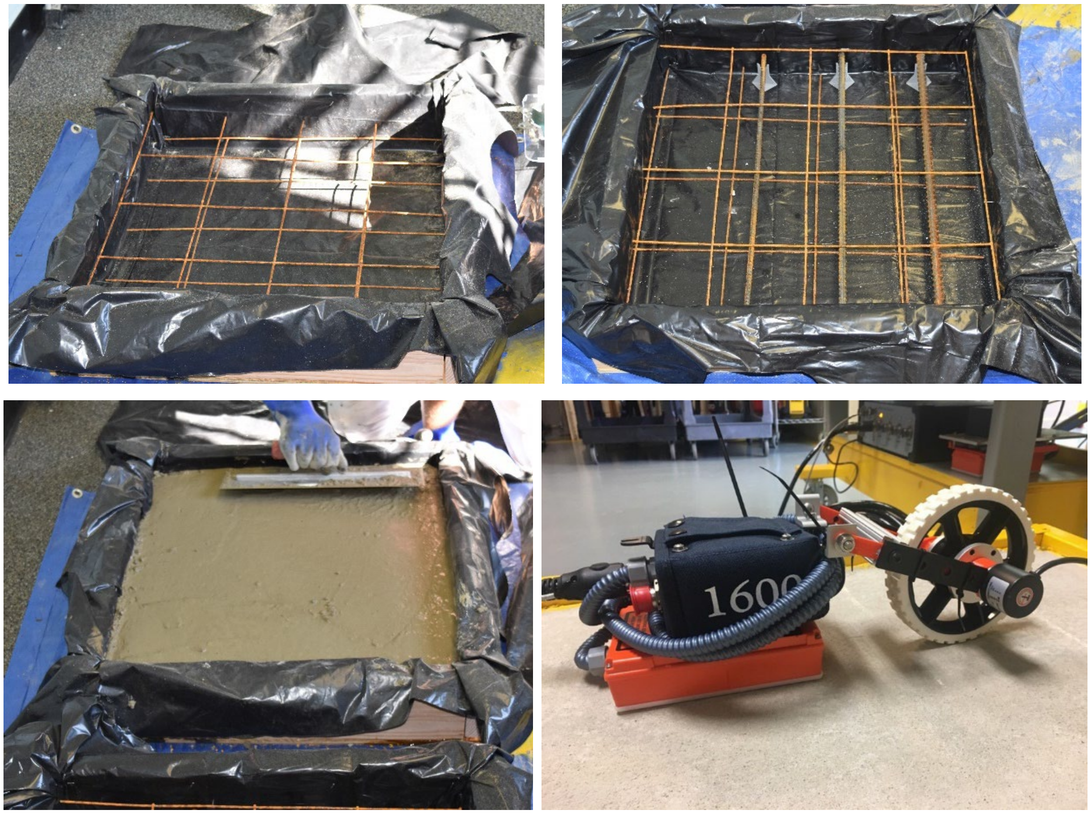


Figure 3 - Lab Setup

The project team conducted two different sets of GPR tests with both ground-coupled and air-launched antennas on the concrete blocks with the aim of determining the rate of moisture ingress over time using the concrete blocks and exposing the blocks to uniform amounts of moisture ranging from 0.08” to 0.4” on the surface.

After processing and analyzing the results, it was determined that monitoring the rate of moisture ingress using GPR over time is not granular enough to study the rate at which moisture ingresses throughout the depth of the concrete. This technique was also deemed not feasible for the field implementation as it would require frequent scanning of the sample for an extended amount of time. As a result, the project team is now using the dielectric constant values as measured by the air-launched GPR system as a measure of the moisture content of the sample under investigation.

The GPR equipment used for this test were GSSI ground-coupled and air-launched GPR antennas with 1.6 GHz and 2 GHz center frequencies.

The surface imaging and crack mapping systems were already tested vigorously in the field and thus did not require lab testing as the results were significantly promising and capable of meeting the demanding accuracy and resolution of this research.

CALCULATION OF DIELECTRIC CONSTANT AND DATA QUALITY

The GPR system that is being used for this research is an air-launched 2 GHz GPR system, which is capable of estimating the dielectric constant of the area under investigation with relatively high accuracy after sensor calibration. This GPR system calculates the dielectric constant of reinforced concrete through a series of sophisticated steps. The system emits high-frequency electromagnetic waves from an antenna towards the concrete surface. When these waves encounter interfaces within the concrete, such as rebar, part of the wave is reflected back to the receiving antenna. By accurately measuring the time delay (time-of-flight) and the amplitude of the reflected signals, the system can determine the velocity of the electromagnetic waves within the concrete.

The dielectric constant (ϵ_r) is inversely related to the wave velocity (v) through the equation:

$$v = \frac{c}{\sqrt{\epsilon_r}}$$

Where c is the speed of light in a vacuum. By analyzing the travel time of the waves and applying this relationship, the dielectric constant of the concrete can be calculated. This constant provides insights into the concrete's material properties, such as moisture content and density, which are crucial for assessing the structural health and integrity of the bridge deck. Advanced data processing techniques enhance the accuracy and reliability of these measurements. Since all of the bridge decks under investigation were recently constructed, it is assumed that the rebars are still in good condition and the corrosion cycle has not begun or barely begun, which calls for the rebars to act as perfect reflectors for the GPR signal. As a result, the variabilities of the signal will be directly correlated with the condition of the concrete above them.

Data Quality

In order to utilize the GPR data confidently for this endeavor, we should ensure the quality of the GPR signal is as good as it can be. As a result and through collaboration with GSSI Inc. (the GPR antenna manufacturer) the project team came up with a series of data quality measures to ensure the collected data meets certain standards before using the data for processing purposes.

For this reason, before any data collection task in the field, the project team conducts a metal plate calibration where a large metal plate (as the perfect reflector) is placed under each GPR antenna, and a series of QA/QC tasks begin. All of the following specifications are based on the GPR reflection from this metal plate. A typical metal plate reflection (MPR) is shown in the figure below. The amplitude of reflection (e.g. volts) is measured from the maximum positive peak to the preceding negative. In the following specification tests no filtering, averaging or signal clean up, such as sky wave removal, shall be allowed.

Figure 4-Metal plate calibration in the field

Performance Specifications:

1. Noise to Signal Ratio Test: The antenna is positioned at its recommended operating height (between 12 and 18 inches) above a minimum sixteen square foot (4' x 4') metal plate. The radar unit is turned on and allowed to operate for a fifteen (15) minute warm up period. After warm-up, the unit is operated at a maximum pulse rate, and fifty (50) radar waveform pulses are recorded. The recorded waveforms are evaluated by the operator for noise to signal ratio. The noise to signal ratio is described by the following equation:

$$\frac{\text{Noise Level}\,(A_n)}{\text{Signal Level}\,(A_{mp})} \leq 0.05\ (5\%)$$

The Signal Level A_{mp} is defined as the average metal plate reflection amplitude as measured from the peak to the preceding minimum. The Noise Level (A_n) is defined as the worst case maximum amplitude occurring between 1 and 10 ns after the surface reflection. The Noise Level is measured from any positive peak to either the preceding or trailing negative, whichever is greater. The Noise to Signal Ratio shall be less or equal to 0.05 (5%).

2. Signal Stability Test: The same test configuration is used as described in the Noise to Signal Ratio test. Fifty (50) traces are recorded at the minimum data rate of 25 traces/second. The signal stability is evaluated using the following equation:

$$\left| \frac{A_{\max} - A_{\min}}{A_{AVG}} \right| \leq 0.01(1\%)$$

where:

A_{max} is defined as the maximum MPR amplitude for all 50 traces.
A_{min} is defined as the minimum MPR amplitude for all 50 traces.
A_{AVG} is defined as the average MPR amplitude of all 50 traces.

The signal stability test results for the GPR shall be less than or equal to 1%.

3. Long Term Signal Stability: The same test configuration is used as described in the Noise to Signal Ratio test. The Radar is switched on with no warm up and allowed to operate for 2 hours continuously. As a minimum, a single waveform shall be captured every 2 minutes, 60 in total. The MPR amplitude shall be calculated and plotted against time. To check for signal drift the time at which the MPR occurs is captured and plotted against time. For the system to be performing adequately the amplitude should remain constant after a short warm up period and the system should have little or no drift.

The stability criteria is as follows:

$$\left| \frac{A_{any} - A_{20}}{A_{20}} \right| \leq 0.03\,(3\%)$$

Where:

A_{20} is the amplitude measured at 20 minutes.
A_{any} is any amplitude measured after 20 minutes.

The drift criteria is as follows:

$$t_{any} - t_{20} < 0.3 \text{ ns}$$

$$\left| t - t_{20} \right| \leq 0.3ns$$

Where;

t_{20} is the time (e.g. in ns) when the peak MPR occurs at 20 minutes
t_{any} is the time when the MPR occurs in any trace after 20 minutes

4. Variations in Time Calibration Factor: The same test configuration is used as described in the Noise to Signal Ratio test, 50 traces are collected and the height of the antenna is measured. The test is repeated at three different heights. Typically heights of approximately 12", 16" and 20 inches are used by the project team for this test. The time delay from the end reflection at the tip of the antenna to the metal plate reflection is measured for each trace and their mean is time t_i (where the subscript represents height position at i). The difference between t_2 and t_1 represents the time to travel a fixed distance in air. The factor C_1 is calculated by dividing the distance by the time difference (e.g. inches per nanosecond). The factor C_2 represents the same between heights 2 and 3. The variation in time calibration factor is as shown below:

$$\left| \frac{C_1 - C_2}{\text{Mean of } C_1 \text{ and } C_2} \right| \leq 0.02\ (2\%)$$

The variation in time calibration factor shall be less than or equal 2%.

5. <u>End Reflection Test</u>: The same test configuration is used in the Noise to Signal Ratio test is used.

5.1 The amplitude of the end reflection directly preceding the MPR is measured. This is a measure of the adequacy of system tuning. The criterion is:

$$\frac{A_E}{A_{mp}} \leq 0.25\ (25\%)$$

Where:

A_E is the mean of the amplitude of end reflection defined as any peak occurring from 1 to 5 nanoseconds before the MPR.
A_{mp} is the mean of the amplitude of reflection from the metal plate.

The end reflection in the metal plate test shall be less than or equal to 25% the amplitude of MPR.

5.2 To avoid having to subtract the end reflection from the signal, this test is designed to ensure that the end reflection does not interfere with the surface reflection. A MPR is collected as specified in the Noise to Signal test. The antenna is then pointed towards the sky and a "sky wave " is captured. When conducting this test the antenna must be at least 20 foot away from metal objects and away from any overhead power lines. The "sky wave " reflection will be aligned with the MPR and subtracted. The MPR amplitude after subtraction is then measured. The criterion is

$$\left| \frac{A_{mp} - A_{mpe}}{A_{mp}} \right| \leq 3\%$$

Where
A_{mp} Amplitude of MPR (See N/S test)
A_{mpe} Amplitude of MPR after removal of sky wave

5.3 (Alternate) A foam block is added below the antenna to increase the time delay of the metal plate reflection (MPF) by at least 3 ns. The average disturbance of the end reflections in the 2 ns time window normally occupied by the MPF is then measured. This disturbance shall be small enough so that:

$$\frac{A_E}{A_{mp}} < 0.05\ (5\%)$$

Where:

A_E is the worst case amplitude of the end reflection disturbance in the 2 ns window.
A_{mp} is the average amplitude of MPR.

6. Symmetry of Metal Plate Reflection. The same test configuration as used in the Signal to Noise Ratio test is used. Two different criteria have been established for symmetry as described below;

6.1 The first criterion is the time from the maximum negative peak following the surface reflection to the zero crossing point is measured. The required specification is:

$$t_f \leq 0.7ns$$

An example of MPR which pass and fail this specification are shown below:

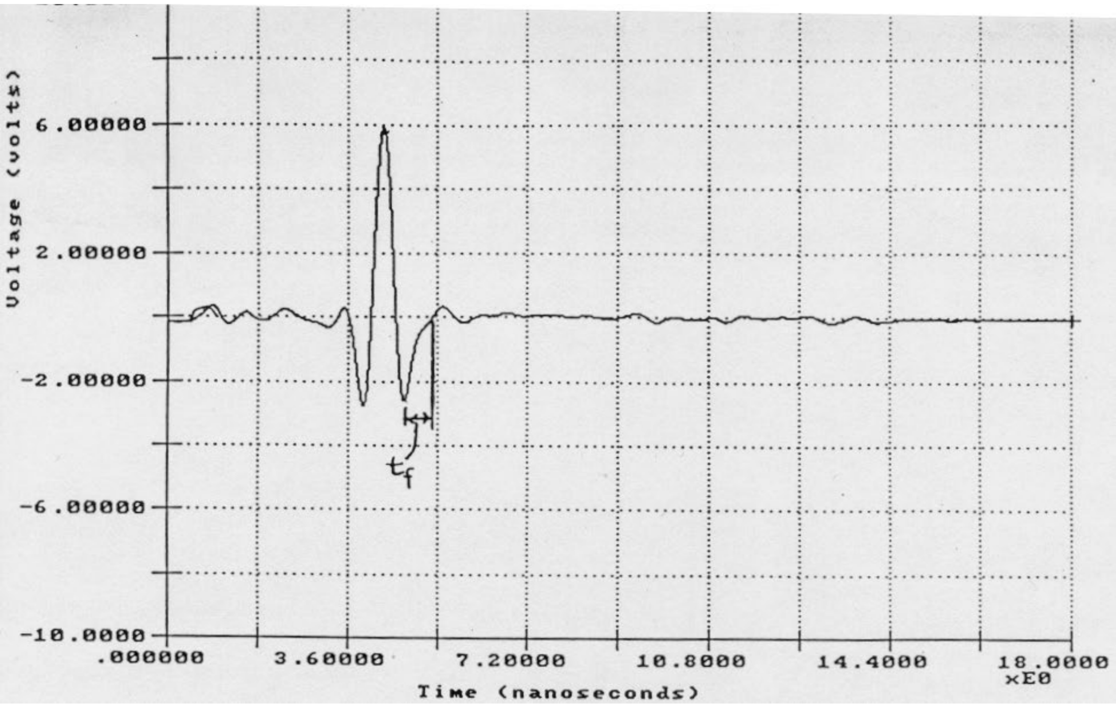


Figure 5-Acceptable metal plate reflection (Courtesy of GSSI Inc.)

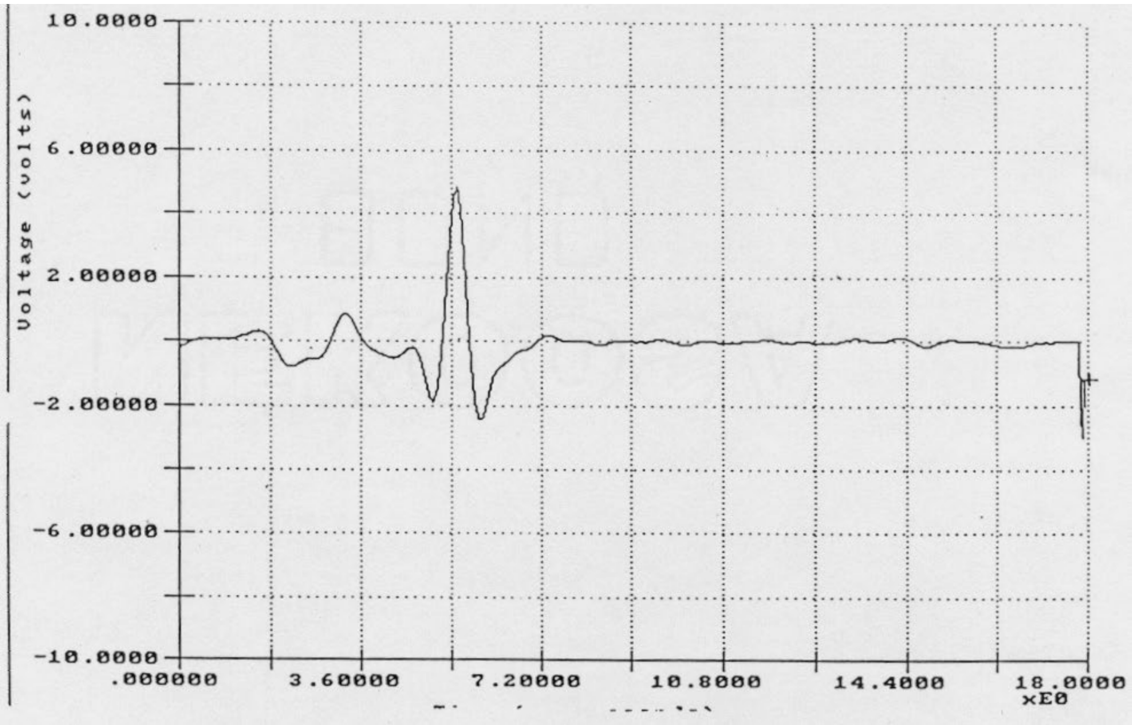


Figure 6-Unacceptable metal plate reflection (Courtesy of GSSI Inc.)

6.2 The second criterion is based on the symmetry of the “legs” of the metal plate reflection. The amplitude is measured from the positive peak to both the preceding and trailing negative. The specification is

$A_{min}/A_{max} > .95$ (95%)

Where A_{min} and A_{max} are the minimum and maximum MPR amplitudes measured using the proceeding or trailing negatives. The ratio should be at least 95%.

Once the above calibrations are successful, the project team will have absolute confidence in the quality of the data that is captured and will be able to use it for the purpose of this research, knowing that the amount of equipment-related error is minimized to the extent possible.

Software Integration and preparation of the crack mapping system

As part of the preparation for the field work, the project team also enhanced the required crack mapping software systems based on artificial intelligence to detect, mark and measure surface cracks on the high-resolution images that are captured by the high-speed data collection system. This AI machine learning system is trained to detect surface cracking in concrete and is capable of finding cracks as small as 0.004” (0.1 mm) in width.

Figure below highlights an output of the crack detection and mapping system where cracks as small as 0.008 in. wide are properly detected and marked. The results are also tabulated and available in Comma Separated Value (CSV) spreadsheets.

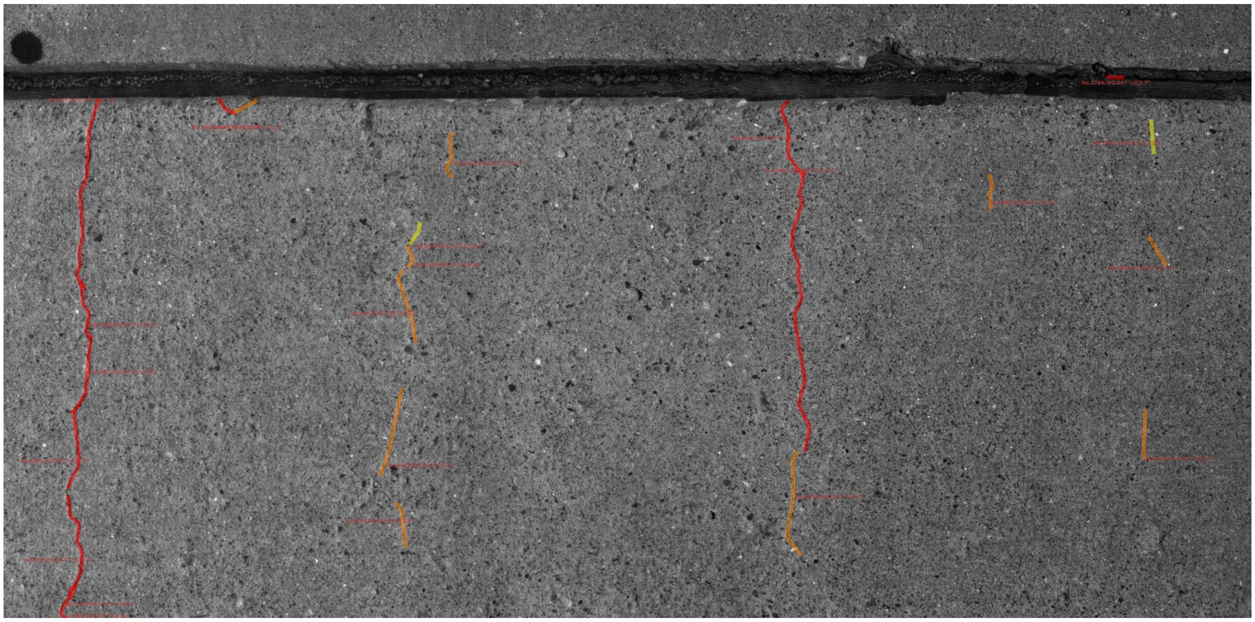
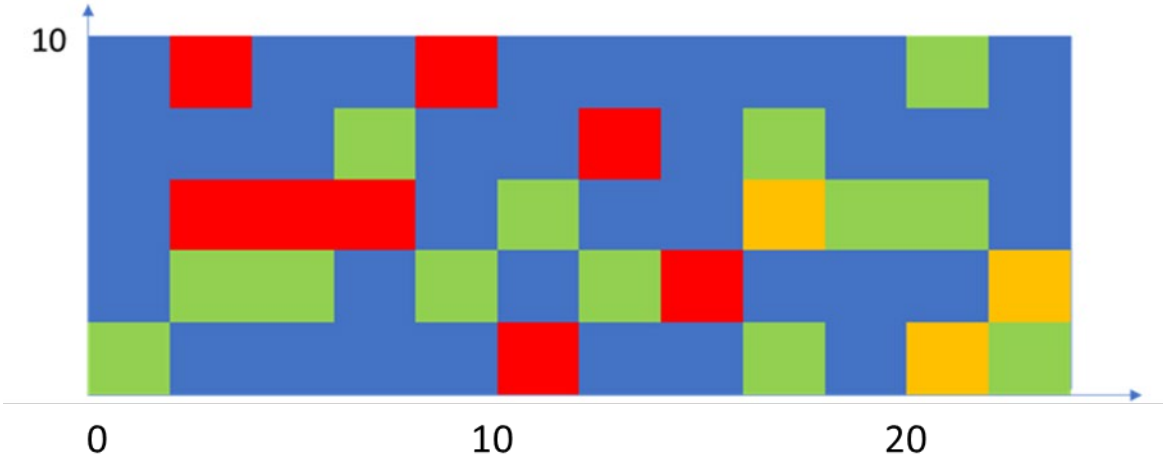


Figure 7-Sample crack map produced by the AI

The other software system that was tailored in-house during this phase to help with the results analysis is capable of ingesting the tabulated crack mapping results of the above system and producing crack density plots that are color-coded based on the crack density criteria that the operator selects. The formula that can generate the crack density plot is variable thus the project team can experiment with different crack density calculation approaches to find the one that produces the highest amount of insight when investigated together with the GPR data.



Low Density (<0.10 ft/ft2), moderate (0.1 to 0.22), severe (>0.22 to 0.37), very severe (>0.37)

Figure 8 - Crack density plot

In the figure above, each square represents a 2’ x 2’ area on the surface and the colors represent the density of the cracks in each unit of the surface area. The crack density is defined as “Total length of cracks within the unit of surface area / unit of surface area”.

The results of the density plotting function are available both in plots as well as data tabulation in CSV formats.

There was also an interesting problem that the project team faced and resolved during the preparation and testing of the crack mapping AI system. The issue was that the AI-based crack detection algorithm falsely detected the new grooves on a bridge deck as cracks. This problem was inherently interesting for the project team as it only happened on new grooves and the algorithm was correctly ignoring grooves on older bridge decks and not identifying them as cracks as shown in the following figure:

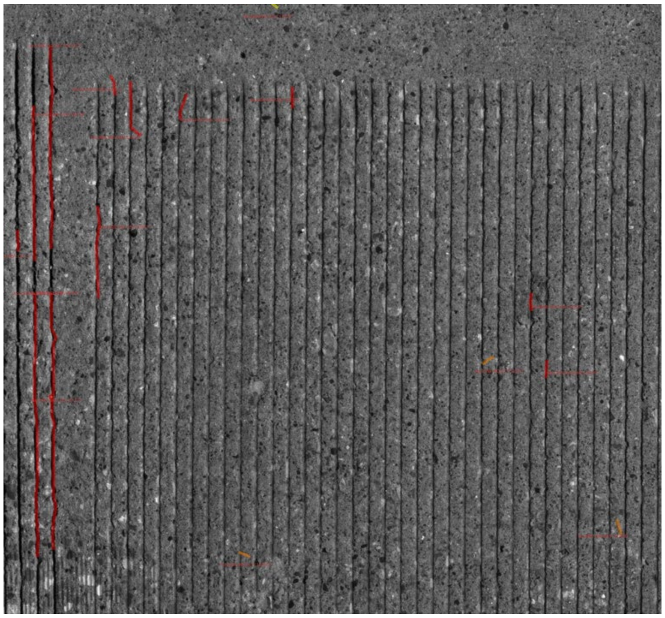


Figure 9-AI crack map, mis categorizing the new grooves

To address this issue, the project team started retraining the AI model on the new grooves. It is evident that the AI algorithm can distinguish between newer and older grooves while falsely categorizing the former as cracks and correctly ignoring the latter as non-cracks. The algorithm retraining started to bear favorable results that are evident in the following figure.

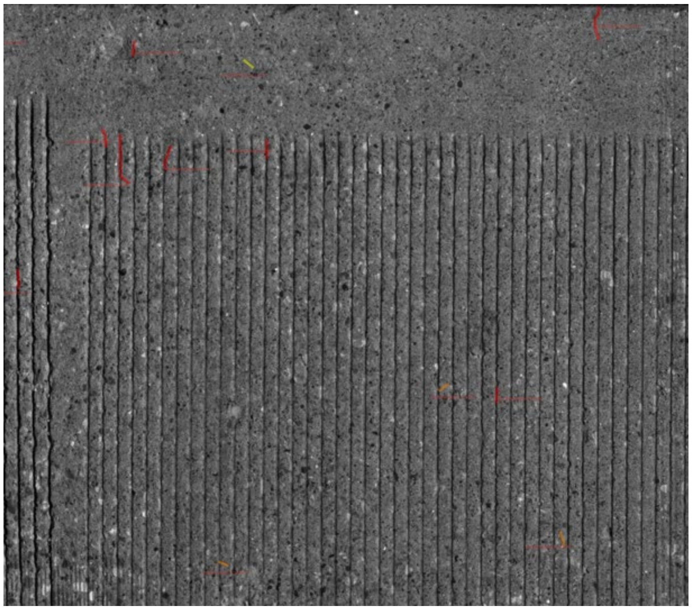


Figure 10 - AI crack map after retraining on the new grooves

STAGE 2. FIELD DATA COLLECTION AND APPLICATION OF THE FINDINGS

As part of this innovative research, comprehensive field data collection was conducted across various states, including Delaware, Texas, Iowa, and Indiana. These diverse geographical locations provided a robust testing ground to validate the methodologies and technologies during the project. Each state presented unique environmental conditions, bridge designs, and construction/preservation practices, enabling a thorough evaluation of the proposed NDE protocols and data collection techniques. These states each are unique in many perspectives.

Some of Delaware's bridge inventory is located in coastal areas where high humidity and saltwater exposure present significant challenges to structural integrity. The winters in the northeast also subject the bridges to freeze-thaw cycles, which subsequently results in the exposure of the decks to salts and chlorides as deicing agents. The data collected here allowed us to test the efficacy of our methods in environments prone to accelerated corrosion and moisture ingress.

Texas, with its vast network of highways and varying climatic zones, offered an opportunity to assess the performance of our techniques in different temperature and humidity conditions.

Iowa's and Indiana's bridges, often subjected to harsh winter conditions and freeze-thaw cycles, provided critical data on the impact of these factors on the bridge deck's condition. The field data collected in Iowa and Indiana was instrumental in refining our approach to address the challenges posed by severe weather fluctuations.

The following table summarizes the field data collection that took place in each state.

#	State DOT Partner	Number of Bridge Decks	Date	Status
1	Iowa DOT	8	Sep 2023	Complete
2	Indiana DOT	8	Nov 2023	Complete
3	Texas DOT	3	May 2024	Complete
5	Delaware DOT	4	May 2024	Complete

Table 1- Data collection plan

The project team collected data from 23 in-service bridges across four states. The help of our state DOT partners was instrumental in planning the field activities and making a great success. The acquired data was then processed using the methods and techniques explained in the prior sections. We will review the results for 6 of the sampled bridges in the following section and discuss the correlation in data as well as the calculation of the vulnerability factors. Please note that the following results exclude the Texas data as the data is still being processed at the time of writing this report due to high environmental noise that affected the GPR data on the selected bridge decks.

The data collection for the Delaware bridges took place in May 2024 and 4 bridges in the Wilmington area were selected for data collection. The project team reviewed the collected data and selected two bridges out of these bridges for further data processing and analysis.

DE Bridge ID: 1714 A347

This bridge deck that was constructed in 2022 already shows evidence of cracking, and as surface conditions show, the cracks have been previously sealed.

Crack Map: (Including the approaches)

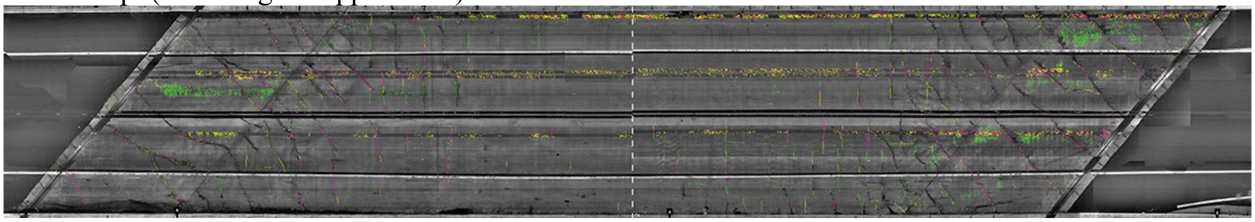


Figure 11-Crack map

Crack Density Plot: (Excluding the approaches)

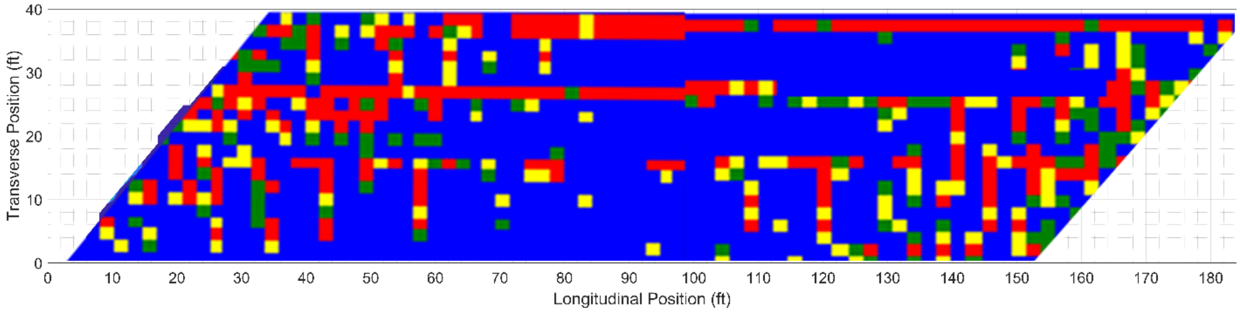


Figure 12-Crack density plot

Di-electric Percentage Change from Background: (Excluding the approaches)

The way this plot is produced is by establishing a background dielectric value for the bridge deck as the average dielectric reading from all the available GPR data. Once the background is established, the percentage change for each data point is calculated and indicated as a color-coded value on the diagram below.

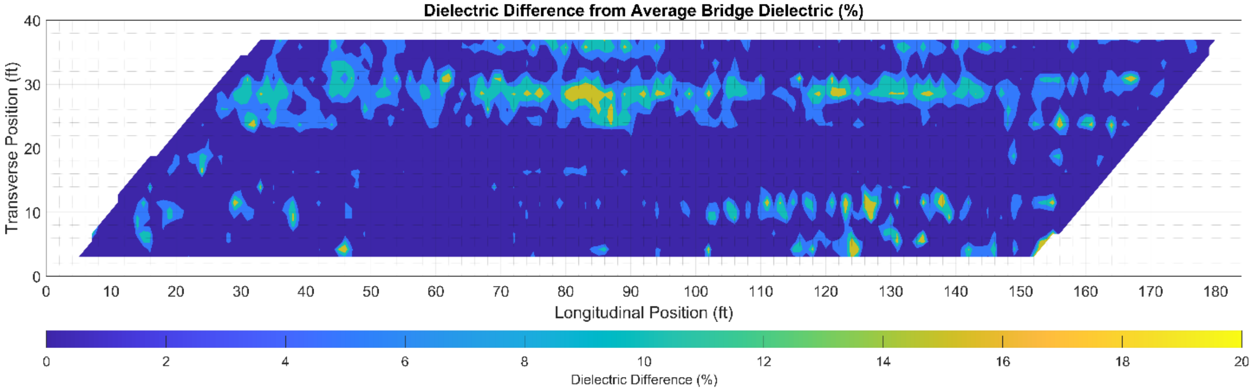


Figure 13- Dielectric difference plot

Crack Density Vs Dielectric Change plot

In this plot, the Dielectric change plot (foreground) is overlaid on the crack density plot (background). The purpose of this diagram is to show the correlation between the locations of the concrete bridge deck that have heightened di-electric value compared to the background in contrast with the areas of higher crack density. The alignment of the two plots indicates very well that the areas with very high crack density already show higher dielectric values, thus facilitating a better environment for the movement of ions and starting the corrosion cycle.

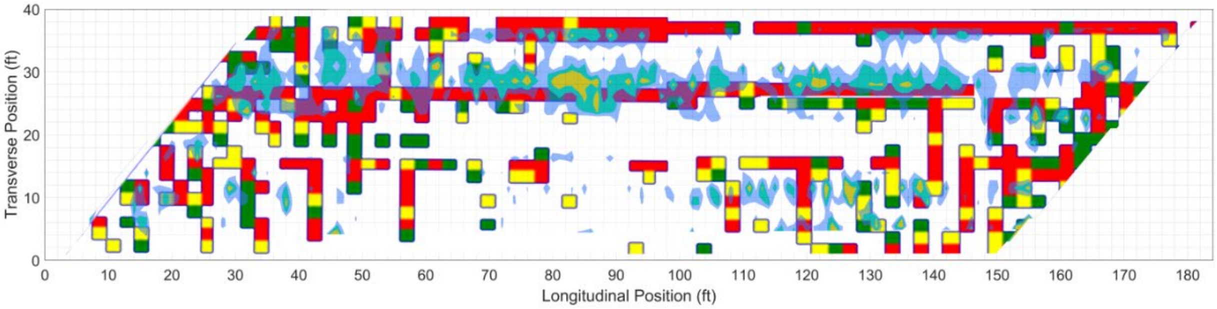


Figure 14-Crack map vs dielectric difference plot

DE Bridge ID: 1714347

Crack Map: (Including the approaches)

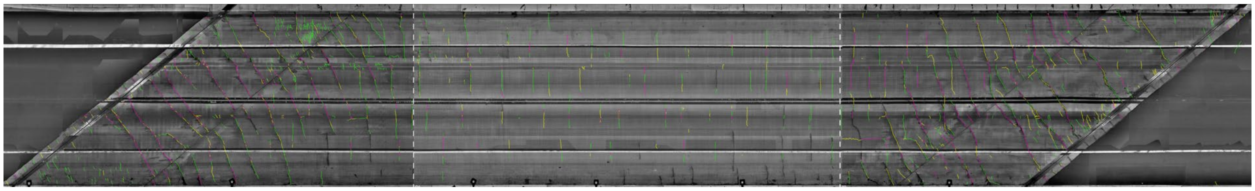


Figure 15 - Crack map

Crack Density Plot: (Excluding the approaches)

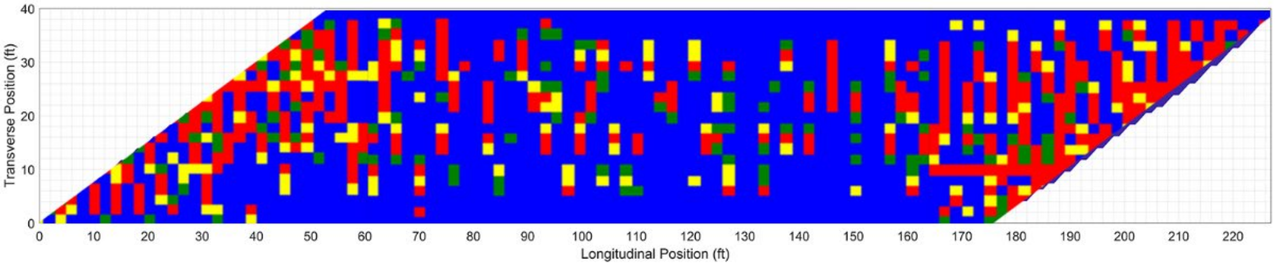


Figure 16-Crack density plot

Di-electric Percentage Change from Background: (Excluding the approaches)

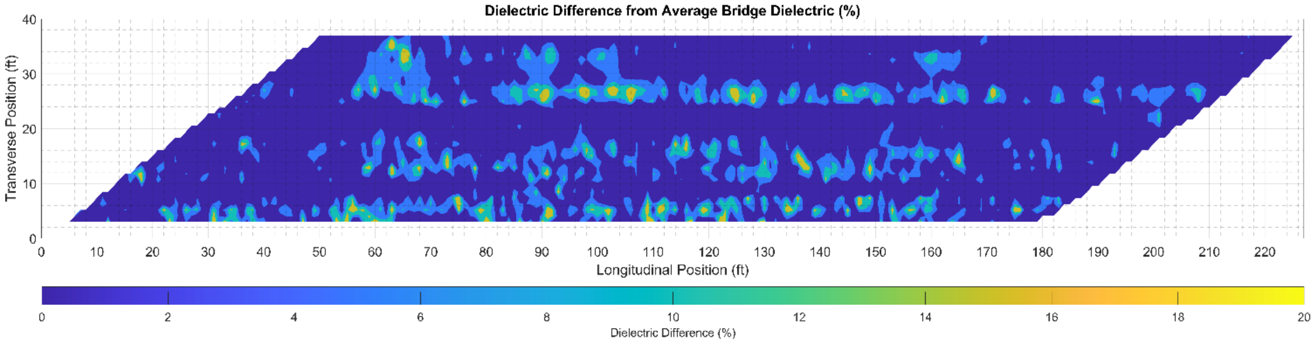


Figure 17- Dielectric difference plot

Crack Density Vs Dielectric Change plot

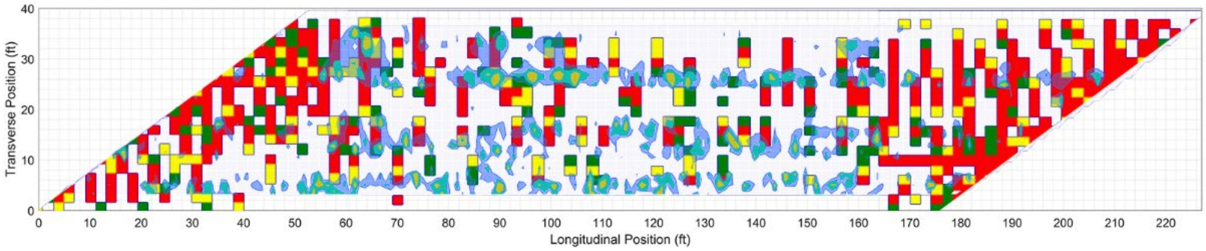


Figure 18-Crack map vs dielectric difference plot

As indicated in the plot above, the areas of higher dielectric value coincide with the longitudinal locations of 55 ft. to 170 ft., where there is a high amount of unsealed surface cracking.

IN BRIDGE ID: 17191

Crack Map: (Including the approaches)

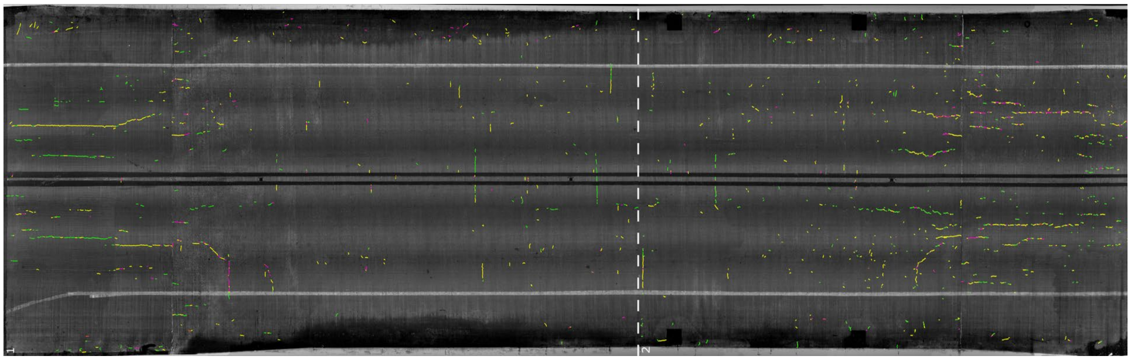


Figure 19 - Crack map

Crack Density Plot: (Excluding the approaches)

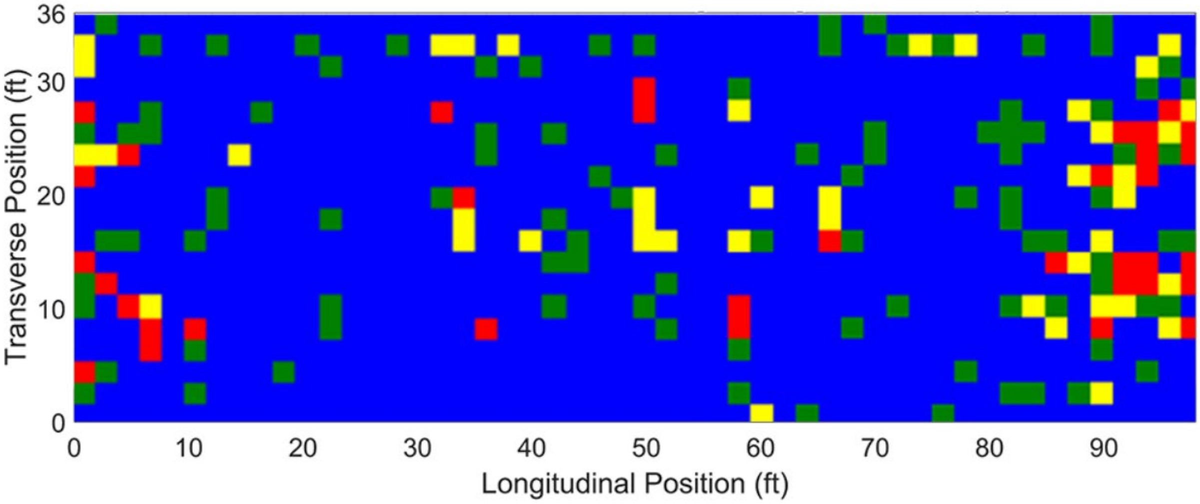


Figure 20-Crack density plot

Di-electric Percentage Change from Background: (Excluding the approaches)

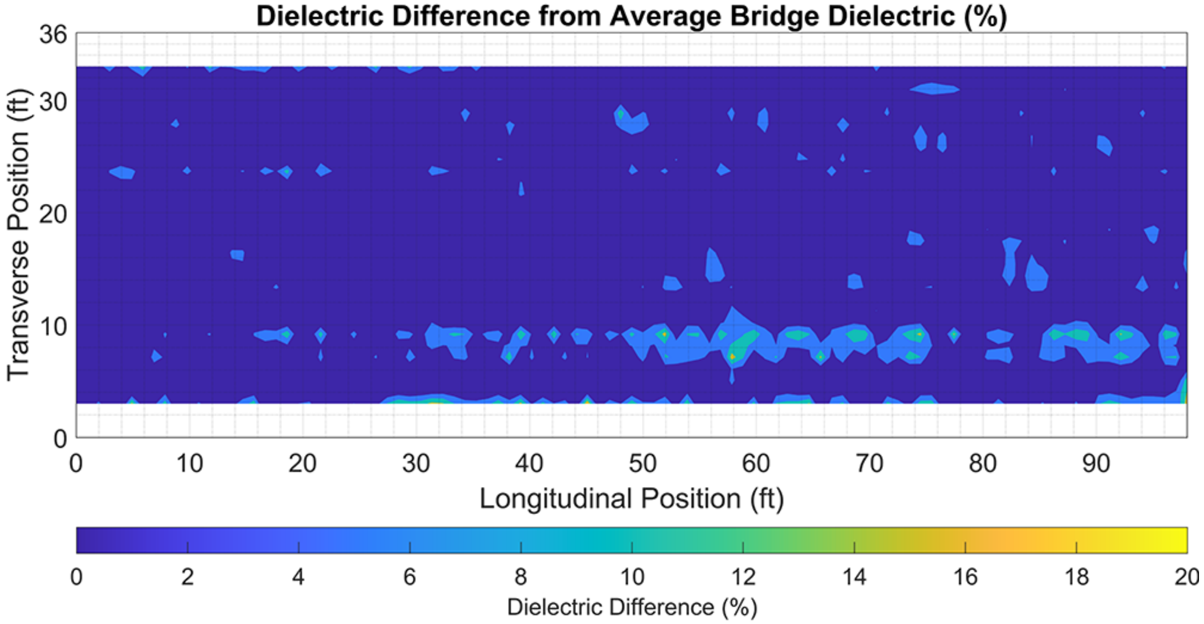


Figure 21- Dielectric difference plot

Crack Density Vs Dielectric Change plot

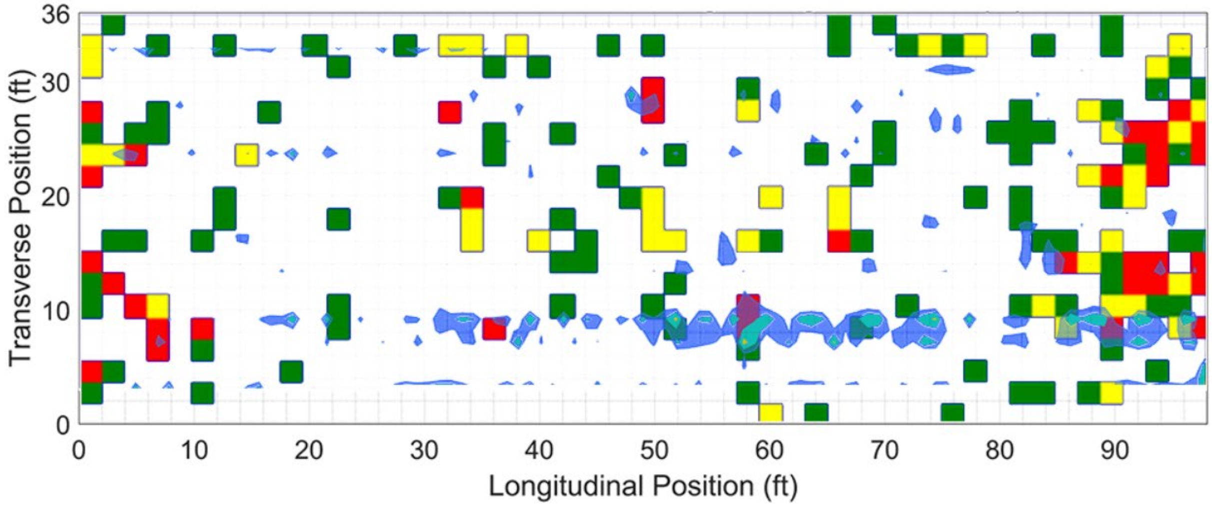


Figure 22-Crack map vs dielectric difference plot

IN BRIDGE ID: 26211

Crack Map: (Including the approaches)

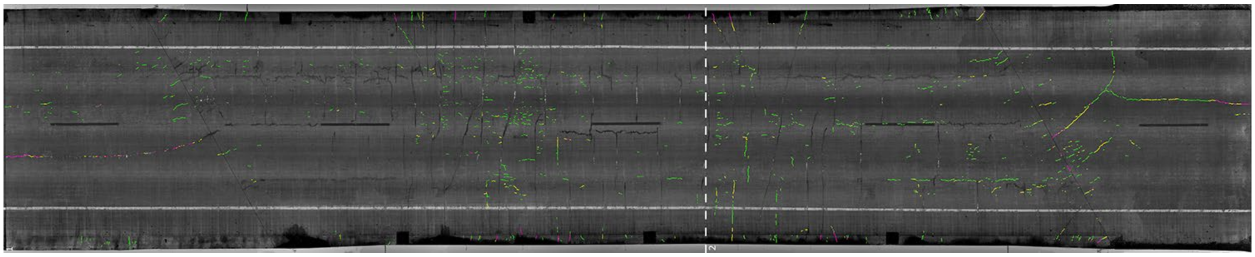


Figure 23 - Crack map

Crack Density Plot: (Excluding the approaches)

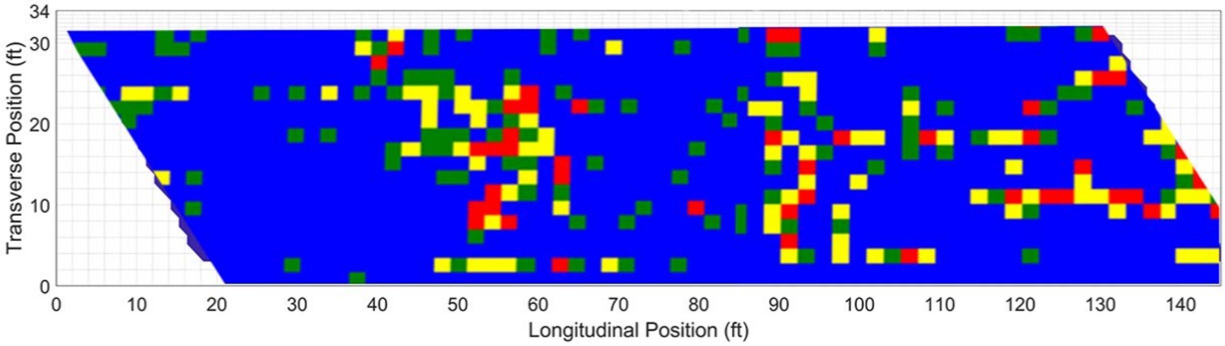


Figure 24-Crack density plot

Di-electric Percentage Change from Background: (Excluding the approaches)

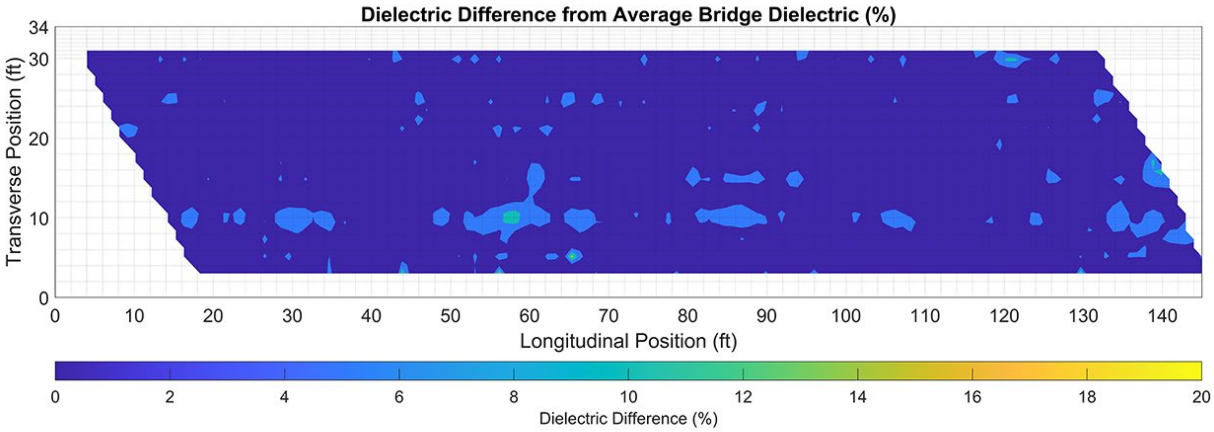


Figure 25- Dielectric difference plot

Crack Density Vs Dielectric Change plot

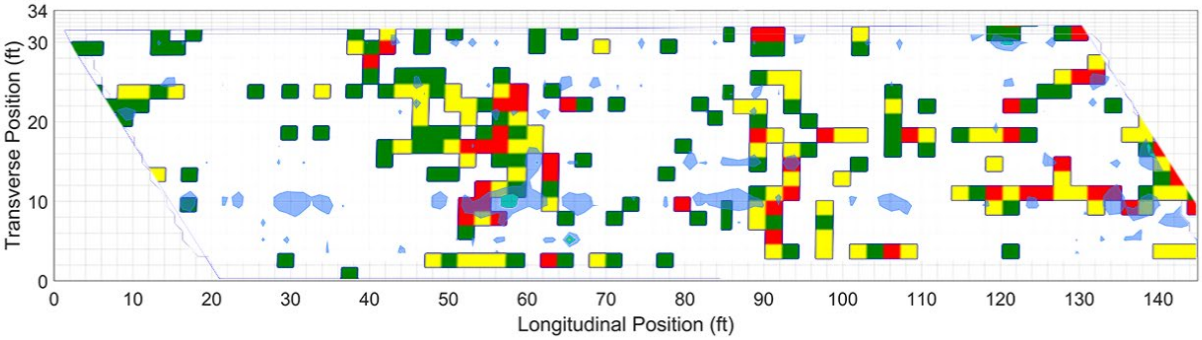


Figure 26-Crack map vs dielectric difference plot

IA BRIDGE ID: 700945

Crack Map: (Including the approaches)

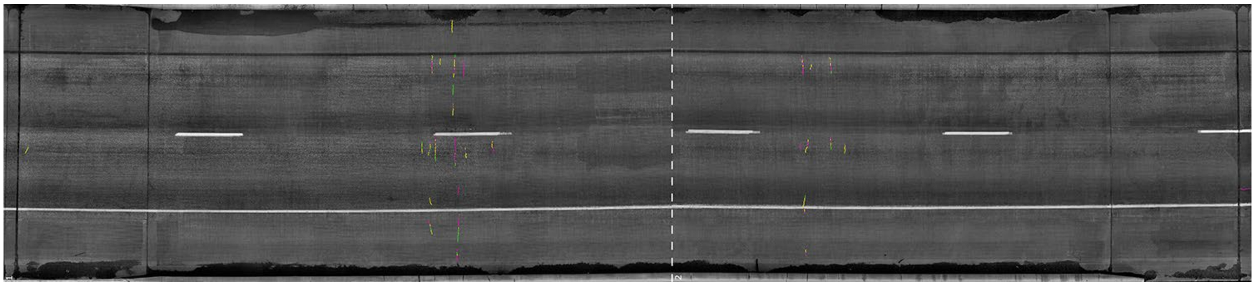


Figure 27 - Crack map

Crack Density Plot: (Excluding the approaches)

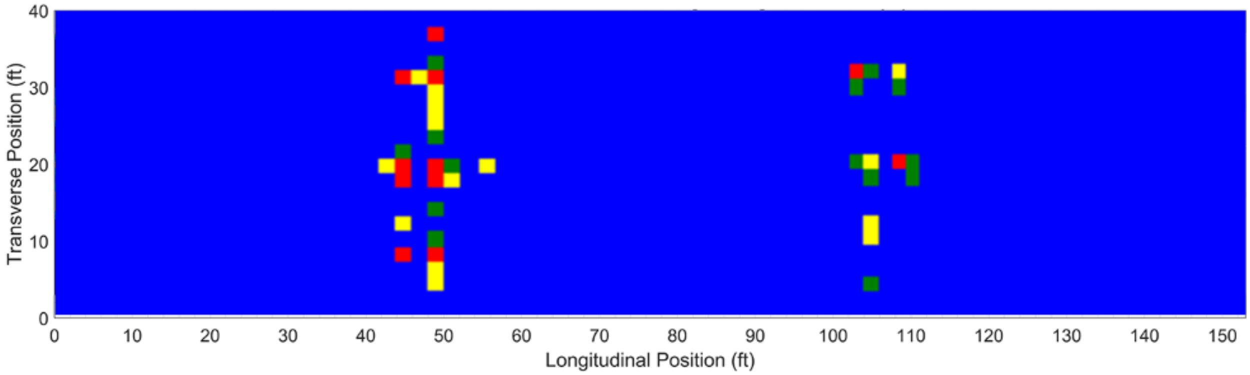


Figure 28-Crack density plot

Di-electric Percentage Change from Background: (Excluding the approaches)

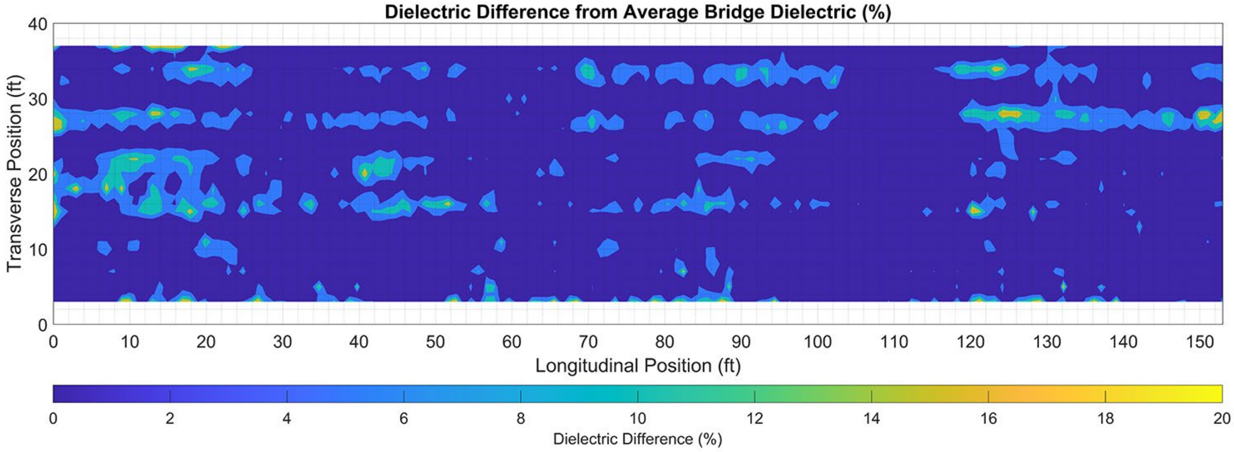


Figure 29- Dielectric difference plot

Crack Density Vs Dielectric Change plot

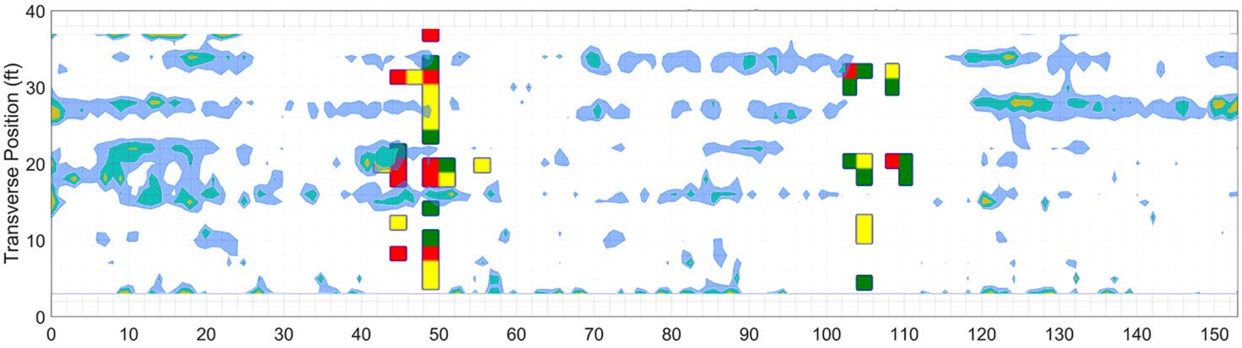


Figure 30-Crack map vs dielectric difference plot

IA BRIDGE ID: 700950

Crack Map: (Including the approaches)

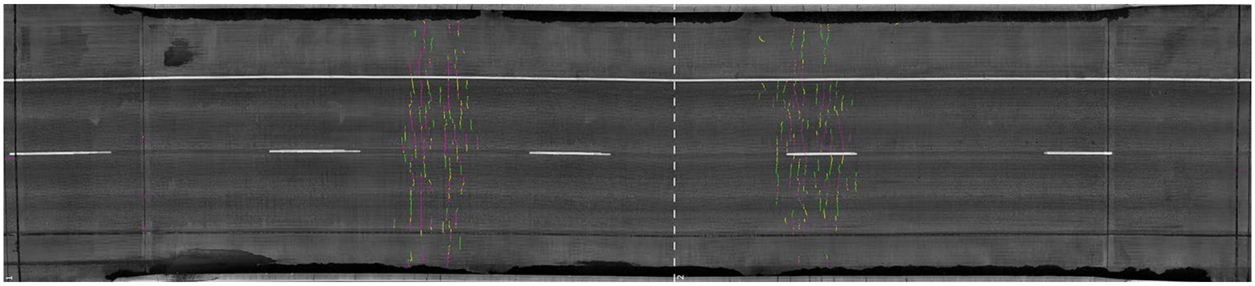


Figure 31 - Crack map

Crack Density Plot: (Excluding the approaches)

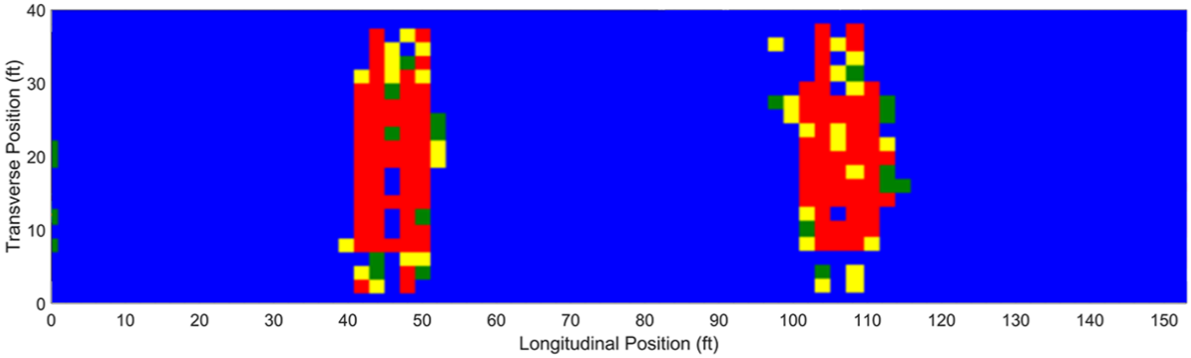


Figure 32-Crack density plot

Di-electric Percentage Change from Background: (Excluding the approaches)

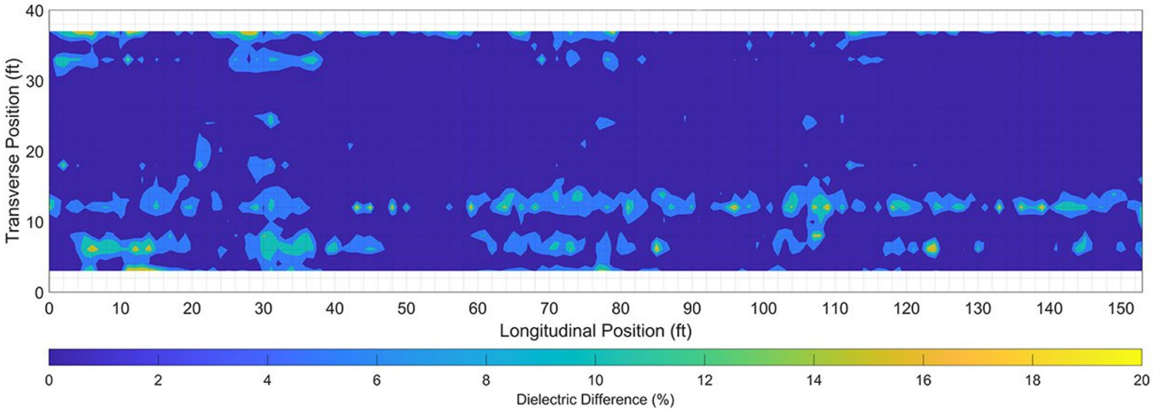


Figure 33- Dielectric difference plot

Crack Density Vs Dielectric Change plot

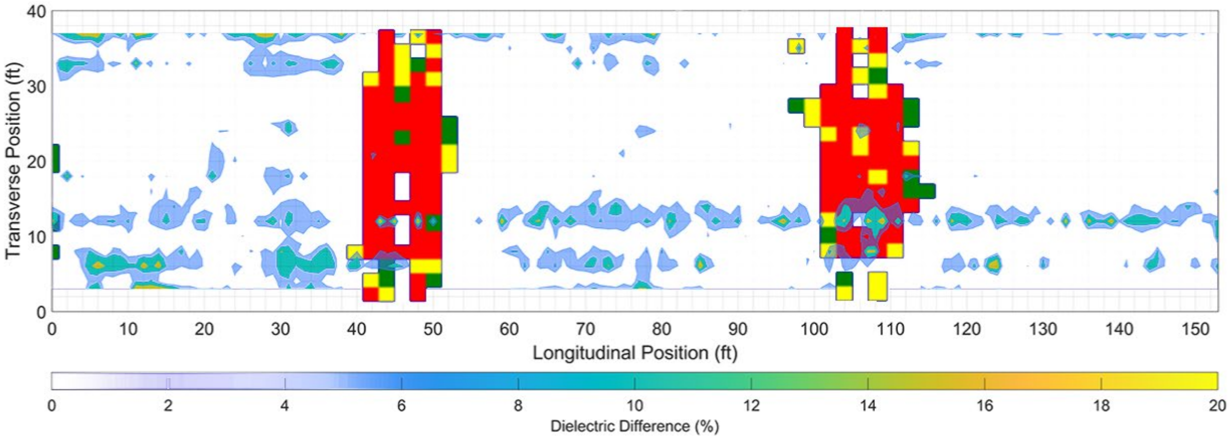


Figure 34-Crack map vs dielectric difference plot

VULNERABILITY INDEX CALCULATIONS

In order to calculate the vulnerability factor, we divided the crack densities into four categories, as seen in the above plots. The density is the total length of the cracks over the surface area of the bridge deck. There is also a weight assigned to each category, which is increasing as the categories worsen to account for the increased severity of the category as the crack density and increase in the dielectric contact is heightened.

Density Label	Crack Density Range (ft/ft2)	Dielectric Increase Compared to Background	Assigned Weight in the formulation (W_x)
Low	<0.10	0% - 7%	0.125
Moderate	0.1 to 0.22	7%-14%	0.25
Severe	0.22 to 0.37	14%-21%	0.375
Very Severe	>0.37	>21%	0.5

Table 2- Equation variables and thresholds

With the above considerations, a proposed formula to calculate the vulnerability index is as follows:

$$VI= W_1 \text{ x } (CD_1 + DE_1) + W_2 \text{ x } (CD_2 + DE_2) + W_3 \text{ x } (CD_3 + DE_3) + W_4 \text{ x } (CD_4 + DE_4)$$

Where:

- VI is the Vulnerability Index.
- Wx is the assigned weight indicated in the table above.
- CD_x is the percentage of surface area corresponding to the respective crack density.
- DE_x is the percentage of surface area corresponding to the respective dielectric constant. increase

Calculating the vulnerability index for the bridges under investigation returns the following results:

Bridge ID	Vulnerability Index
DE 1714347	0.352
DE 1714A347	0.352
IN 17191	0.294
IN 26211	0.290
IA 700950	0.295
IA 700945	0.282

Table 3-Vulnerability index per bridge deck

Please note that the numbers provided above are merely examples of how the vulnerability index calculation can be applied. As previously discussed, the VI equation has significant potential for refinement, and the indices presented may not accurately reflect the actual field conditions.

PLANS FOR IMPLEMENTATION

In the pursuit of advancing bridge deck preservation strategies, our research project has developed an innovative Non-Destructive Evaluation (NDE) method tailored for a data-driven approach to early-age bridge deck preservation. Leveraging advanced technologies such as refined data analysis of Ground Penetrating Radar (GPR), and high-resolution surface imaging with an automated trained algorithm for crack mapping, this method aims to provide state DOTs and other bridge owner organizations with a reliable and repeatable data-driven tool to identify and prioritize bridge decks according to the vulnerability index explained above. The implementation of these methods promises significant cost savings and extended service life for bridge decks. This section addresses critical questions related to the adoption and implementation of this innovative technology, offering insights into its benefits, challenges, and real-world applicability.

TARGETED AUDIENCES AND BENEFICIARIES

The primary targeted audiences for this technology include state DOTs, toll authorities, and other bridge owner organizations responsible for maintaining bridges. Adopters of this technology will also include private engineering firms and contractors specializing in bridge inspection and maintenance. By implementing this technology, the asset owners will have access to an objective performance measure that can inform them on the current cracking and moisture ingress of their recently constructed structures.

BARRIERS TO ADOPTION

Several barriers to adoption may exist, both perceived and actual. Perceived barriers include skepticism about the effectiveness of new technologies compared to traditional methods, concerns about the initial costs, and potential disruption during implementation. Actual barriers might include the need for specialized equipment, the integration of new information into existing workflows, and decision-making processes for selecting bridges for preservation purposes. Addressing the equipment barrier through a service model can pave the way for mass adoption through the elimination of capital expenditure, as no ownership of specific equipment by the DOTs would be required.

CASE STUDIES AND PILOT TESTING

Our research included comprehensive field data collection in Delaware, Texas, Iowa, and Indiana, which served as pilot studies to validate the methodologies and technologies developed during the project. These diverse geographical locations provided a robust testing ground to ensure the effectiveness of the technology in various environmental and operational contexts. The successful implementation of the technology in these pilot studies demonstrated its practical applicability and operational benefits.

STATE CHAMPIONS AND STAKEHOLDER ENGAGEMENT

Several state DOTs, including those in Delaware, Texas, Iowa, Indiana, Vermont, and Wisconsin, have expressed interest and participated in our advisory committee and pilot testing. The project team remains hopeful that these DOTs will champion and share the results of this study with other state DOTs to ensure more engagement and adoption by asset owners.

CONCLUSIONS

Through the successful development and pilot testing of the proposed NDE methods in this study, the project team has demonstrated the potential to transform the current approach to scoring and selection of bridge decks for preservation purposes. This methodology provides a more objective and data-driven approach to identifying early deterioration triggers that are often missed by conventional inspection techniques.

Throughout this research, several important lessons were learned. One key insight is the importance of customizing NDE methodologies to account for environmental and structural variances across different bridges and geographical regions. This adaptability ensures the accuracy and relevance of the collected data. Additionally, the integration of AI-based data processing to detect, measure, and categorize cracks has proven to be a powerful tool for generating detailed crack maps, offering a new level of precision in bridge deck surface assessment.

Another lesson learned is the critical role of collaboration with state DOTs and industry partners. Their feedback and participation were invaluable in refining our methodologies and ensuring the proposed innovation's practical and field applicability.

The innovative use of NDE technologies in this research holds significant potential for breakthroughs in transportation practice. By providing early, reliable indicators of bridge deck vulnerabilities, these methods enable proactive maintenance strategies that can extend the service life of bridges and reduce maintenance costs.

To achieve the implementation of the project results, a clear path has been established. This includes ongoing collaboration with state DOTs to validate the methodologies in diverse operational environments and to refine the technology based on real-world feedback. Training programs will be developed to equip bridge inspectors and maintenance personnel with the necessary skills to use the new NDE tools effectively.

APPENDIX: RESEARCH RESULTS

Sidebar Info

Program Steering Committee: NCHRP IDEA Program Committee
Month and Year: June 2024
Title: Establishing NDE Protocols for Use in Early Age Bridge Deck Preservation Strategies

Project Number: NCHRP 243
Start Date: January 2023
Completion Date: June 30, 2024

Product Category: IDEA NCHRP

Principal Investigator:
Amir Rezvani, Project Manager
E-Mail: amir@infrateksolutions.com
Phone: (732) 881-1265

TILTE:
Establishing NDE Protocols for Use in Early Age Bridge Deck Preservation Strategies

SUBHEAD:
Assessed, designed and developed nondestructive evaluation (NDE) triggers based on hairline crack mapping of surface images as well as moisture retention in concrete bridge decks

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WHAT WAS THE NEED?

According to FHWA, "a successful bridge program seeks a balanced approach to preservation and rehabilitation/replacement. Bridge owners are striving to be more strategic by adopting and implementing systematic processes for bridge preservation as an integral component of their overall asset management.". However, the current inspection methods are not capable of identifying the need for bridge preservation activities at the right time. As a result, they are often delayed beyond their most effective timelines for maximum benefit. The need for a data-driven, objective method to help bridge owners determine and prioritize their assets based on their performance post-construction has never been as pressing as right now.

WHAT WAS OUR GOAL?

The primary goal of this study was to develop and establish advanced protocols for the early-age preservation of bridge decks using Non-Destructive Evaluation (NDE) methods. The objective was to create a reliable, data-driven approach to detect and quantify early signs of deterioration that are often undetectable by conventional inspection techniques. By leveraging advanced NDE technologies such as Ground Penetrating Radar (GPR) and High-Resolution Surface Imaging with Automated Crack Mapping, the study aimed to identify vulnerabilities in bridge decks at an early stage, thus enabling timely and effective maintenance interventions.

WHAT DID WE DO?

In this study, we developed and implemented advanced protocols for early-age bridge deck preservation using Non-Destructive Evaluation (NDE) methods. We conducted laboratory and field permeability tests to measure water penetration and retention in concrete decks under varying environmental conditions. Advanced NDE techniques such as Ground Penetrating Radar (GPR), high-resolution surface imaging with AI-based crack mapping, were employed. These methods allowed us to track moisture retention, detect hairline cracks, and monitor dielectric constants in concrete bridge decks. We processed these data sets using AI algorithms and integrated them to create detailed vulnerability indices that assess the condition state of bridge decks using the factors above.

Field data collection was carried out on bridge decks in Delaware, Texas, Iowa, and Indiana. We collaborated with state DOTs and industry partners to fine-tune our methods and ensure their practical applicability. Feedback from state DOTs helped us refine our techniques, and pilot testing validated our protocols in real-world scenarios.

WHAT WAS THE OUTCOME?

The study demonstrated that these advanced NDE methods are effective in identifying early signs of deterioration through producing of the vulnerability index, enabling timely maintenance interventions, extending the service life of bridge decks, and reducing long-term maintenance costs.

WHAT WAS THE BENEFIT?

The primary benefit of this study is the development of early-age bridge deck preservation triggers using NDE metrics. This proactive approach allows for timely preservation activities, preventing minor issues from escalating into major repairs or replacements. As a result, this can lead to substantial cost savings, reducing maintenance costs and increasing the service life of the structure.

Additionally, the development of a comprehensive vulnerability index provides a robust, data-driven assessment of bridge deck conditions, enabling more informed decision-making. This tool helps infrastructure managers prioritize maintenance activities based on the severity of detected issues that are generally concealed from the inspectors, ensuring that the bridge decks that can benefit from preservation activities receive attention first. Overall, the benefits of this study include extending the service life of bridge decks, optimizing maintenance budgets, and enhancing the overall selection procedure for bridge preservation activities.