A NOVEL FORENSIC STUDY OF DOWEL BAR ALIGNMENT USING NON-DESTRUCTIVE METHODS

Aleks K. Kivi, MASc, P.Eng.
Senior Pavement Engineer
Applied Research Associates, Inc.
2904 South Sheridan Way, Suite 103
Oakville, ON L6J 7L7
akivi@ara.com

Paper prepared for the session "Innovations in Pavement Management, Engineering and Technologies"
2024 Transportation Association of Canada (TAC) Conference & Exhibition
Vancouver, British Columbia

Acknowledgements
The author would like to acknowledge the invaluable contributions of all project collaborators, particularly Lori Schaus, MASc, P.Eng., in the organization and execution of the work presented in this paper.

A NOVEL FORENSIC STUDY OF DOWEL BAR ALIGNMENT USING NON-DESTRUCTIVE METHODS

ABSTRACT

Dowel bars are used in the construction of jointed concrete pavements to provide load transfer across transverse joints, which is a vital factor in achieving good long-term performance. Misaligned or improperly placed dowels may cause poor joint performance, which can lead to the development of distresses, such as cracking, spalling or faulting. Many agencies include requirements for the verification of dowel bar alignment at the time of construction to ensure that any misalignments can be immediately repaired.

This paper presents a forensic case study involving the novel use of two types of non-destructive testing equipment performed on an Ontario roadway to evaluate the severity and extent of errors in dowel bar placement known to have been made during a concrete paving project. Specifically, the MIT-SCAN device, a scanner employing magnetic imaging tomography principles, and a step-frequency array Ground Penetrating Radar (also known as 3D GPR) were used to evaluate the position and alignment of the dowel bars in hundreds of transverse joints.

Using the results of the two methods of non-destructive evaluation, conformance with project construction specifications was determined and a repair plan to cost-effectively mitigate the non-compliances was developed. The study's outcome was specific remediation recommendations, including slab replacements, dowel bar sawcuts and dowel bar retrofits, executed to the satisfaction of both the owner and the contractor.

A NOVEL FORENSIC STUDY OF DOWEL BAR ALIGNMENT USING NON-DESTRUCTIVE METHODS

1. INTRODUCTION

Present day standards for Portland cement concrete (PCC) pavements generally include the placement of control joints at appropriate locations to prevent random pavement cracking. However, these joints create a discontinuity in the pavement.

Traffic loadings must be effectively transferred from one slab to the next, i.e., across the discontinuity, to reduce edge and corner deflections and the resulting stresses and strains. This is necessary to ensure acceptable pavement performance by preventing the development of distresses. Poor load transfer may result in distress such as faulting, cracking and corner breaks. Examples of good and poor load transfer are illustrated in Figure 1.

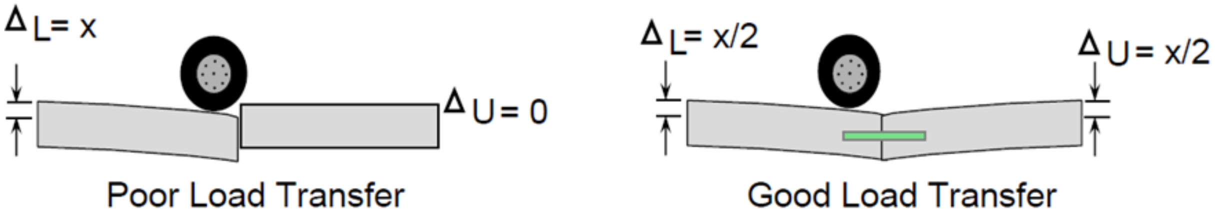


Figure 1: Load transfer efficiency principle

Dowel bars are typically used at transverse joints to assist in providing load transfer and prevent faulting, except in low volume, light traffic scenarios. The dowels reduce the deflections at the joints, thereby by minimizing the slab stresses at the critical corner locations. The provision of effective load transfer is a key design element for jointed concrete pavement and proper dowel bar placement is an important factor in ensuring good performance. One component of good pavement performance is proper dowel bar position and alignment.

2. JOINTS AND DOWEL BAR ALIGNMENT

To control the magnitude of stresses at the transverse joints, standard modern construction practice is to install cylindrical steel dowel bars spaced at regular intervals along the length of the joint (typically 300 mm centre-to-centre spacings). For highways, the dowels are typically 32 to 38 mm in diameter and have a length of 450 mm (FHWA 2019).

The expectation is that dowel bars are installed parallel to the vertical and horizontal planes of the pavement. The bars should be placed at the mid-depth of the slab and centered longitudinally along the sawcut. Improper placement may not only reduce the effectiveness of dowel bars, but may also contribute to premature distress formation, including joint spalling and slab cracking.

There are two main methods of dowel bar installation during construction: the use of dowel basket assemblies or the dowel bar inserter (DBI). Dowel baskets are steel truss structures, fabricated from thick wire and used to hold dowel bars at the appropriate height and position prior to the placement of the fresh concrete. The dowel baskets are laid out and anchored to the underlying base course prior to being paved over. A dowel basket assembly is shown in Figure 2.

Figure 2: Dowel Basket Assembly

The dowel bar inserter is a device mounted on a slipform paver. At each transverse joint location, the DBI automatically inserts the dowels into the fresh concrete along the length of the joint. The DBI pushes the dowels to the appropriate depth and consolidates the concrete around the dowel locations using vibrating forks. A dowel bar inserter is shown in Figure 3.

Figure 3: Dowel Bar Inserter on Slipform Paver

Any deviations in dowel bar position from the ideal position may be defined as misalignment. Dowel bar misalignments can be grouped into five generalized categories (Tayabji 1986):

- horizontal translation;
- vertical translation;
- longitudinal translation (side shift),
- horizontal skew (rotation); and
- vertical tilt (rotation).

The five types of bar misalignment are shown in Figure 4.

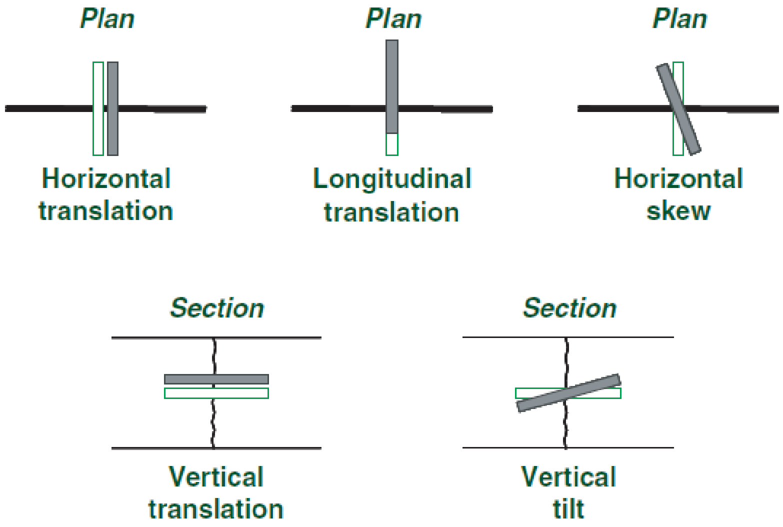


Figure 4: Types of Dowel Bar Misalignment (after Tayabji 1986)

Rotational misalignments, i.e., skew or tilt, generally impact the global free movement of joints, while translational misalignments generally impact the effectiveness of individual dowel bars in providing load transfer.

Bar misalignment can occur for various reasons during construction. These reasons may be related to materials, equipment or workmanship. For dowel installations using baskets, possible reasons include, but are not limited to, insufficient basket rigidity; poor quality control during basket fabrication, e.g., loose welds or improper heights; damage during basket transportation and placement; improper basket anchoring; and inaccurate placement of sawcuts over the basket (Tayabji 1986).

While the perfect alignment of each dowel bar is desirable, practical limitations in construction processes exist. Some degree of misalignment can be deemed acceptable as the detrimental effects resulting from minor misalignments are not likely to occur. Many agencies specify dowel bar position and alignment tolerances that balance the practical limitations of equipment, workmanship and material properties, and also the critical levels of misalignment that are likely to result in distress formation.

3. METHODS OF EVALUATING DOWEL BAR ALIGNMENT

Various non-destructive methods have been developed for the evaluation of dowel bar position and alignment of in-service pavements. These methods allow for the measurement of dowel bar position, easily and accurately. Two methods employed in the case study presented in this paper are described below.

3.1. MIT-SCAN

The MIT-SCAN device, manufactured in Germany, transformed the state-of-the-art for the determination of dowel bar positioning and alignment using non-destructive means. Using the principles of magnetic tomography, the MIT -SCAN device emits a weak, pulsating magnetic signal and subsequently detects the induced eddy currents in the embedded dowel bars. Using sensitive detectors and sophisticated data analysis algorithms, the position of the dowels can be calculated with great accuracy (Yu and Khazanovich, 2005).

The MIT-SCAN system (MIT-SCAN-2) consists of three main components:

- The scanner unit that emits electromagnetic pulses and detects the induced magnetic field using five sensor coils;
- An onboard computer that runs the operates the system, collects the test data, and performs the preliminary evaluation (originally wired, subsequently wireless in the Bluetooth-enabled version);
- A glass fiber-reinforced plastic rail system that guides the scanner unit along the joint.

An example of the MIT-SCAN-2 in use along a transverse joint is shown in Figure 5. The operator aligns the rail system along any transverse joint. After initiating the test on the handheld computer, the operator pulls the wheeled scanner carriage on the rails along the length of the joint using a rope. The onboard computer, running the MagnoNorm software, will collect the measuring signals resulting from the embedded dowels and will generate the measurement results for most joints directly in the field.

Figure 5: MIT-SCAN-2 Device in Use

More comprehensive analysis of the data can be performed using the MagnoProof software. Using the higher computing power of Windows-based systems, MagnoProof can calculate the positions of bars in more complicated measuring situation, e.g., greater degrees of misalignment or the influence of foreign metal. The MagnoProof software also produces graphic outputs, of which an example is shown in Figure 6. The heat maps provide a three-dimensional visual representation of the dowel positions.

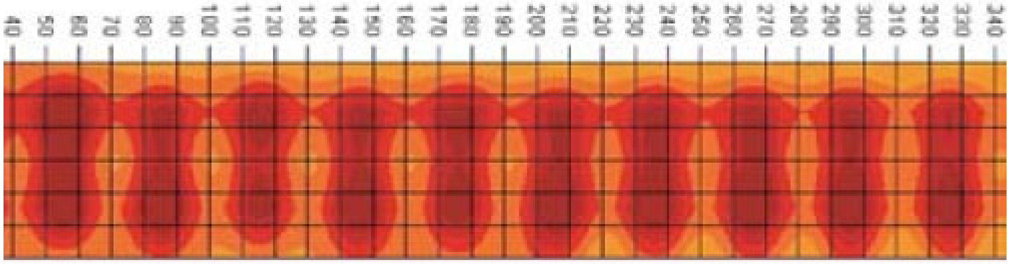


Figure 6: Example Graphical Output from MagnoProof showing Dowel Bars

Each MIT-SCAN device is individually calibrated to the types of dowel bars that will be scanned using the device in order to provide accurate results. The bar calibrations take into consideration the bar material, diameter and length.

3.2. Ground Penetrating Radar

Ground Penetrating Radar (GPR) systems operate by transmitting pulses of electromagnetic energy into the ground and then recording the energy that is reflected back to the surface. The GPR signal responds to variations in the electrical properties of subsurface materials, i.e., dielectric constant and conductivity, that are a function of material type and moisture content. Where a contrast in dielectric properties exists between adjacent materials, a proportion of the electromagnetic energy will be reflected back. Subsurface structures can be mapped by measuring the properties of this reflected energy, i.e., amplitude and travel time. Figure 7 shows an example of a transverse scan of a joint using ground coupled equipment. The dowel bars are shown as hyperbola shapes.

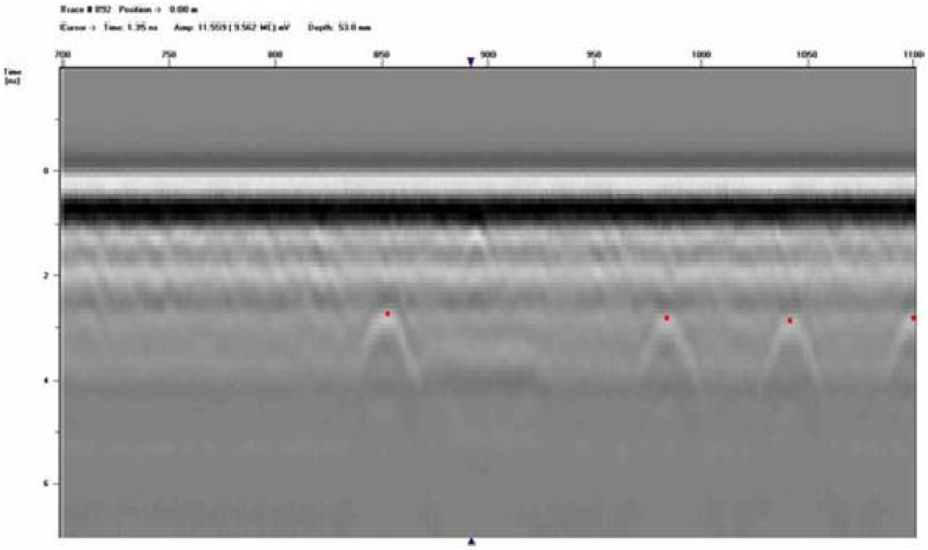


Figure 7: GPR Scan of Concrete Pavement Transverse Joint

While studies (MoDOT 2003) have shown that that GPR can be used to assess dowel bar alignment accurately, GPR data processing is a complicated activity and not automated like the MIT-SCAN equipment. While the Missouri Department of Transportation demonstrated that vertical alignment can be accurately measured within 3 mm and lateral dowel position can be measured within 10 mm, it must be noted that an experienced analyst is needed to interpret the GPR output and compute the dowel bar positions.

3.2.1. 3D GPR

Wide-array GPR, also known as 3D GPR, is a recent development that provides numerous benefits over traditional GPR systems. The step-frequency multi-channel 3D GPR antenna array, manufactured by Kontur AS of Norway (formerly known as 3D-Radar), scans up to a 3.3 m wide swath using equally spaced GPR sensors, effectively providing continuous GPR data of the areas surveyed. Unlike traditional GPR system that employ single-frequency pulsed antennas, the 3D GPR radar system sweeps through a range of frequencies at each scan point, from 150 MHz to 3 GHz, providing higher resolution and greater depth of penetration in a single pass. The 3D GPR system can be paired with air-coupled (DX series) and ground-coupled (DXG series) antennas that range in width from 0.9 m to 3.3 m. In each antenna, the transverse channels are spaced every 75 mm across the width of the array which scan the subsurface simultaneously through a range of range of frequencies.

Like traditional GPR systems, the 3D GPR system is mounted to a tow vehicle, either directly to a trailer hitch receiver or towed using a trailer, depending on the antenna type. The system is also equipped with a Global Positioning System (GPS) to collect location information using Real Time Kinematic (RTK) corrections, as well as a distance measurement instrument (DMI) attached to the wheel of the vehicle. ARA's 3D GPR system in use is shown in Figure 8.

Figure 8: 3D-GPR Ground Coupled Antenna Mounted to Data Collection Vehicle

4. CASE STUDY

4.1. Background

As part of a highway construction contract, three separate sections of a Canadian highway interchange ramp were reconstructed using jointed plain concrete pavement. To provide mechanical load transfer, dowels had been installed in basket assemblies. Immediately following construction, the highway agency expressed concerns regarding the placement of the dowel baskets.

The project's concrete pavement construction specification included the use of the MIT-SCAN equipment for quality control. Four parameters were evaluated as part of the dowel bar alignment verification: depth, side shift, horizontal misalignment and vertical misalignment. A specification limit was established for each parameter. The applicable tolerances are shown in Table 1.

Table 1: Specification Limits for Position and Alignment of Dowel Bars

Attribute	Lower Limit	Upper Limit
Horizontal Misalignment	-15	15
Vertical Misalignment	-15	15
Side Shift	-50	50
Depth	Mid-depth - 12	Mid-depth + 15

The total quantity of concrete pavement placed on the contract was considered a lot, and each transverse joint was considered a sublot. With respect to dowel bar alignment, acceptance of the lot was set out to be based on the mean and standard deviation of the lot measurements for vertical alignment, horizontal alignment, side shift and depth. The specification allowed for the exclusion of the dowel bar closest to the tied longitudinal joints from the analysis due to possible interference of the tie bar. In accordance with the local construction specification, the dowel basket's transport wires were cut prior to the placement of the concrete. Uncut transport wires (tie wires, shipping wires) are known to reduce the accuracy of the MIT-SCAN data.

Acceptance was based on the "percent within limits" (PWL) for the lot for each of the measuring parameters. If the lot PWL is greater than or equal to 90%, the lot is acceptable. If the lot PWL is less than 90% and greater than or equal to 50%, the lot is accepted with a price adjustment. If the lot PWL is less than 50%, the lot is rejectable and subject to repair and reassessment.

Given the possible consequences of poor construction quality relating to dowel bar positioning and alignment, the highway agency retained ARA to determine the dowel bar positions using the MIT-SCAN-2 device to establish the severity and extent of the dowel bar issues by scanning all of the joints.

4.2. MIT-SCAN Results

ARA evaluated 100% of the joints on three newly sections of concrete pavement totalling 2,028 m in length. A total of 503 joints were scanned. For each dowel bar, five parameters were reported using the equipment's XYZ Cartesian coordinate system: the x-position (position of the bar along the joint), bar depth, horizontal misalignment, vertical misalignment, and side shift. Heat maps were also generated for each joint scanned to provide a visual representation of the bar positions. Each parameter was compared to the project tolerances previously shown.

The results indicated a large degree of variability in the bar positions along the three highway sections. While the MIT-SCAN results indicated large numbers of bars with position and alignment outside of the allowable tolerances, the extent and underlying cause of the bar position errors was hard to qualify using the tabular data alone.

We note that the MIT-SCAN-2 device is optimized to provide the most accurate results around typical specification limits. The measurement error is higher for more severely misaligned bars, and in certain cases of high misalignment, the numbers may not be representative of the actual misalignment. The manufacturer's stated measurement accuracy is listed in Table 2.

Table 2: Measurement Accuracy of MIT-SCAN-2

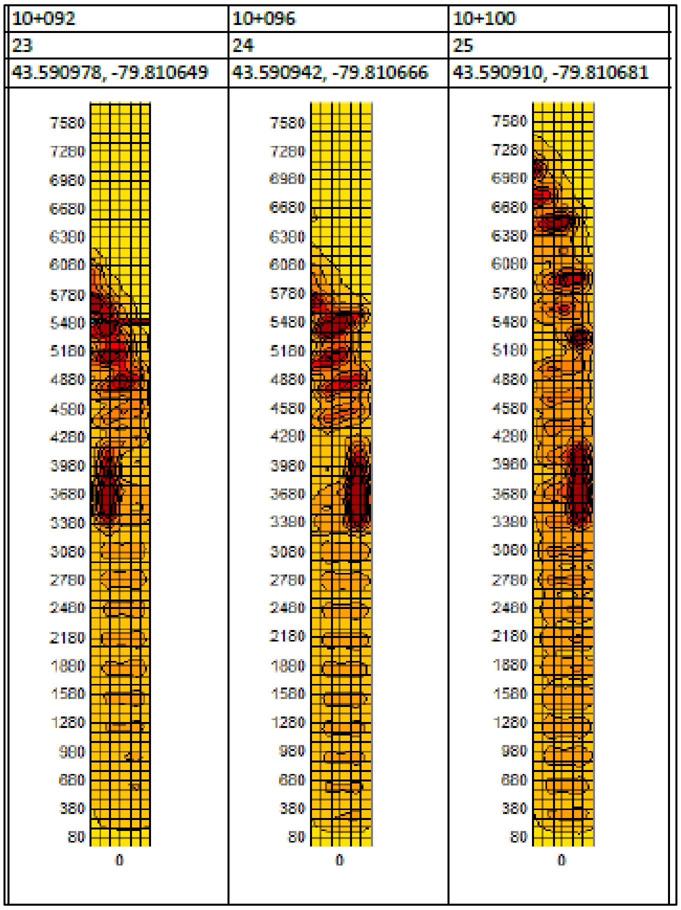
Element	Value
Reproducibility	+/- 2 mm
Measuring length (x-direction)	0.3% +/- 3 mm
Distance between dowels	+/- 4 mm
Rotation (xy plane)	+/- 4 mm
Lateral shift	+/- 8 mm
Depth (cover)	+/- 4 mm
Tilt (xz plane)	+/- 4 mm

This measuring accuracy is valid for the following conditions: horizontal misalignment less than 40 mm; vertical misalignment less than 40 mm; and side shift less than 80 mm. Many joints where the measurements exceeded these values were identified as part of this assignment.

To quantify the issues at hand, ARA reviewed the heat maps generated by the MagnoProof software one-by-one. The heat maps were able to provide a more thorough, albeit qualitative description of the bar positioning errors that had occurred.

From the heat maps, it was possible to see that numerous dowel baskets had experienced gross twisting and displacement, likely due to poor anchoring of the baskets. Also, many joints were identified having tie bars suspected to be in close proximity to the transverse joint. The project construction specification required that tie bars not be placed within 600 mm of a transverse joint. The analysis software attempts to resolve the additional metal introduced by the tie bar as a dowel bar position, therefore, the reported values where tie bars are creating interference may not be representative of the actual dowel bar position values.

Examples of the bar position errors seen in shown in Figure 9. The results for three joints, each comprising two 3.75 m wide lanes are shown. At the top of the heat map, the rotation or twisting of the far end of the dowel basket assembly can be observed in these three joints. Near the middle of the map, at the approximate location of the longitudinal joint between the two lanes, a vertical red object can be shown, which is believed to be a deformed tie bar. The tie bar, which overlaps the dowel bars, is seen to be too close to the transverse joint.



10+092	10+096	10+100
23	24	25
43.590978, -79.810649	43.590942, -79.810666	43.590910, -79.810681

Figure 9: MIT-SCAN Heat Maps Showing Basket Rotation and Tie Bars Too Close.

The consequences of the observed bar misalignments were manyfold. Missing dowels due to the displacement of the baskets away from the transverse joints would provide no mechanical load transfer. Low or non-existent load transfer can cause faulting and cracking. The horizontal and vertical skew of dowel bars can introduce sufficient restraint at the joint to cause cracking. The presence of deformed tie bars too close to the transfer joints can also cause joint lockup, which can also lead to cracking or spalling.

4.3. Validation using Ground Penetrating Radar

Following the receipt of the MIT-SCAN results, the contractor undertook their own efforts to validate the actual bar positions and alignment using additional non-destructive means. Traditional, single-channel ground penetrating radar (GPR) and a concrete cover meter were used to verify the placement of the exact locations of the dowel bars. After completing their testing, the contractor expressed some concerns about the challenges in correlating their data with the MIT-SCAN results and proposed additional coring to verify locations requiring repair. ARA acknowledged that the large misalignments caused by the twisted and displaced baskets, and the interference caused by the close proximity tie bars likely are impacting the accuracy of the individual bar parameters, but emphasized that the list of joints found to have gross dowel misalignment or tie bar interference remained accurate.

Following discussions with the highway agency, ARA proposed to complete multi-channel, wide-array Ground Penetrating Radar (GPR) using our 3D-GPR equipment to assess the dowel and dowel basket alignment along one of the highway sections. The intention of the GPR survey was to provide general confirmation of the MIT-SCAN testing previously completed. While the current state of GPR technology cannot provide the same millimeter accuracy measurements of dowel bar position and alignment with the same ease as the MIT-SCAN device, GPR technology can readily indicate general position and alignment of the baskets (including identifying gross misalignment), indicate the position of baskets relative to joint saw cuts and identify locations with missing bars.

The proposal was accepted by the agency, and ARA carried out the survey using a 1.5 m wide ground-coupled 3D GPR antenna to maximize the resolution of the data. The data collection was conducted at low speeds (25 km/h) to maximize the data quality. Four overlapping passes were performed to collect GPR data from outside pavement edge to inside pavement edge.

An example comparison of the results from the two non-destructive testing equipment are shown in Figure 10 and Figure 11. Figure 10 shows the characteristics of the dowel bars in eight consecutive transverse joints, collected using the 3D GPR system. Figure 11 shows the same eight joints as evaluated using the MIT-SCAN device. Each transverse joint comprises two 3.75 m wide lanes and one concrete shoulder 3.0 m wide. Both sets of results show a large degree of rotation/displacement of the dowel basket in the outside driving lane (near the top of the images).

A thorough review of all the pairwise MIT-SCAN data and GPR data was performed. In general, the GPR plan view scans were found to be consistent with the MIT-SCAN heat maps in identifying areas of gross misalignment of the embedded dowel baskets. This was sufficient to convince the agency and the contractor that the bar misalignments reported by the MIT-SCAN results were accurate. Subsequently, the data was used to develop a remediation plan.

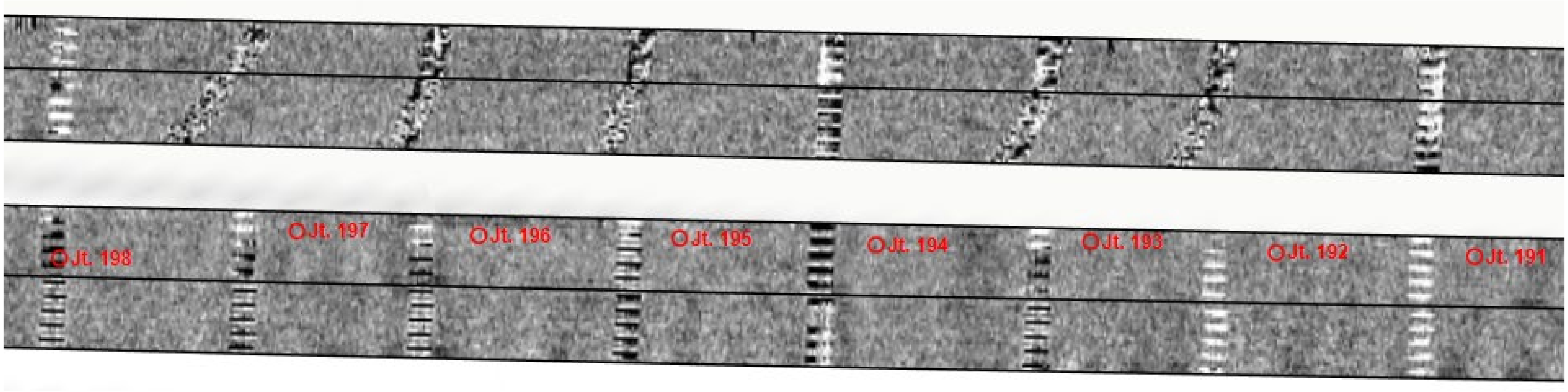


Figure 10: GPR Survey Plan View – Eight Consecutive Joints

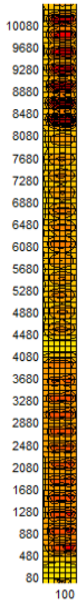
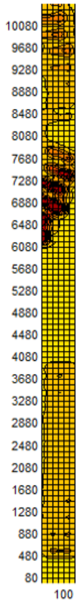
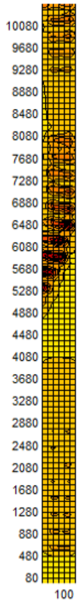
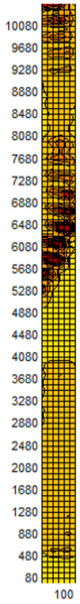
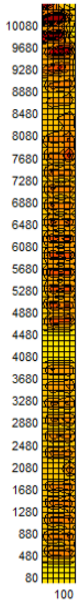
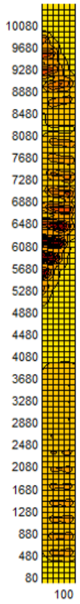
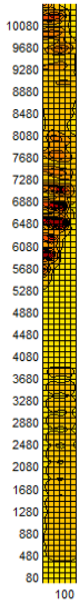
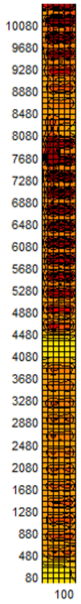
Station	10+792	10+788	10+784	10+780	10+776	10+772	10+768	10+764
Joint No.	198	197	196	195	194	193	192	191
GPS Coordinates	43.585295, -79.814949	43.585339, -79.814934	43.585370, -79.814916	43.585405, -79.814897	43.585440, -79.814878	43.585477, -79.814859	43.585509, -79.814840	43.585544, -79.814821
Map								

Figure 11: MIT-SCAN Heat Map Plan View – Eight Consecutive Joints

4.4. Remediation Plan

The nature of the dowel bar position errors required immediate intervention. While the highway agency had the right to reject the entire lot of concrete pavement for each highway sections, the areas with severely misaligned bars were relatively localized, resulting in the agency to permit the contractor to develop a repair plan. Full removal and replacement would have had considerable impacts to the traffic capacity of the highway and would have likely been delayed for half a year with the impending arrival of the winter season.

Using the non-destructive testing results, the contractor's engineers developed a remediation plan. The recommended activities included in the plan comprised full depth repairs, dowel bar retrofits, sawcutting of dowel bars, and sawcutting of tie bars. In the most severe cases, where the dowel baskets had been considerably displaced, full depth repairs were specified. In areas where the joints in question only had one or two bars out of alignment, or where the tie bar was overlapping the dowels, sawcutting was recommended. Where dowel bars were locally missing out of alignment, dowel bar retrofits were specified.

With input from the agency and their consultants, a plan was developed to remediate the issues resulting from dowel bars missing or out of position, while also preventing the occurrence of further damage by addressing the issues in a timely fashion and return the highway to service with minimal disruptions.

5. CONCLUSIONS

Dowel bar alignment is a key performance indicator for concrete pavements. Non-destructive measurements technologies allow for the detailed evaluation of in-situ dowel bar positioning. When deviations in dowel bar alignment from specification requirements were suspected on a construction contract, two technologies: the MIT-SCAN device and the 3D GPR system were used to identify the problem areas and develop a remediation plan to cost-effectively mitigate the non-conforming areas, to the satisfaction of both the owner and the contractor.

6. REFERENCES

Federal Highway Administration (FHWA). "Concrete Pavement Joints," FHWA Technical Advisory 5040.30. Federal Highway Administration, Washington, DC, 1990

Federal Highway Administration (FHWA). "Concrete Pavement Joints," FHWA Technical Advisory 5040.30. Federal Highway Administration, Washington, DC, 2019

Khazanovich, L., K. Hoegh and M. Snyder. "NCHRP Report 637: Guidelines for Dowel Alignment in Concrete Pavements." National Cooperative Highway Research Program. Washington, DC , 2009

Khazanovich, L and T. Yu. *Use of Magnetic Tomography Technology to Evaluate Dowel Bar Placement*. FHWA-IF-06-002. Tech Brief, Concrete Pavement Technology Program. Federal Highway Administration, Washington, D.C., November 2005.

Missouri Department of Transportation (MoDOT). "Investigation of Dowel Bar Placement Accuracy with a Dowel Bar Inserter". Report RDT-009. Missouri Department of Transportation, Jefferson City, MO, 2003.

Tayabji, S. D. "Dowel Placement Tolerances for Concrete Pavements". *Transportation Research Record No. 1062.* Transportation Research Board, Washington, D.C., 1986.

Yu, H.T. "Real-Time Nondestructive Testing of Dowel Alignment Using MIT Scan-2." AASHTO Construction Subcommittee Meeting, Louisville, KY, 2005.