The Integrated Use of GPR and Conventional Methods for Continuous Pavement Condition Investigations: A Case Study of the QEW Rehabilitation and Widening Project

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ABSTRACT

The Queen Elizabeth Way (QEW) through St. Catharines, Ontario, was originally constructed in the 1930's as a four-lane divided highway with concrete pavements and grassed median. Through the 1950's and 1960's, many of the original at-grade intersections were replaced with grade separated interchanges and the Garden City Skyway was constructed to facilitate travel over the Welland Canal. This portion of the QEW has been resurfaced with asphalt concrete overlays a number of times since the 1950's with the most recent one being carried out in 2004. However, very limited historical records exist for the pavement structure within this heavily trafficked section of QEW.

Functional and structural condition investigation of the existing pavement was undertaken in 2005 and consisted of a visual condition survey of the paved surfaces, soils investigation, asphalt coring, a Falling Weight Deflectometer (FWD) survey and a Ground Penetrating Radar (GPR) survey. Approximately 120 lane kilometres of GPR data were collected to delineate the extent of various pavement structures and estimate type and thickness of the layer materials within each pavement structure.

This paper presents the results of the integration of conventional investigation methods (visual condition survey, boreholes, and asphalt coring) with GPR to generate detailed pavement condition information which was used in developing cost-effective pavement rehabilitation measures for a section of this important traffic corridor. Comparison and correlation of the different data types are presented to demonstrate the effectiveness of the GPR as a supplementary tool to conventional pavement condition investigations in identifying anomalies in the pavement structure and more importantly in reducing the uncertainty in locating changes in buried pavement structure.

INTRODUCTION

The pavement rehabilitation and widening program undertaken beginning in 2005 involves the widening of the Queen Elizabeth Way (QEW) from west of Highway 406 to the west of the Garden City Skyway over a distance of approximately 8.5 km. The QEW Highway links Toronto to New York State through Niagara Falls. The project is located in the City of St. Catharines, in the Regional Municipality of Niagara, as shown on the Key Plan in Figure 1.

This section of the QEW through St. Catharines was originally constructed in the 1930's as a four-lane divided highway with concrete pavements and grassed median. Through the 1950's and 1960's, many of the original at-grade intersections were replaced with grade separated interchanges and the Garden City Skyway was constructed to facilitate travel over the Welland Canal. Several road alignment changes were also made. This portion of the QEW has been resurfaced a number of times since the 1950's with the most recent one being in June 2004.

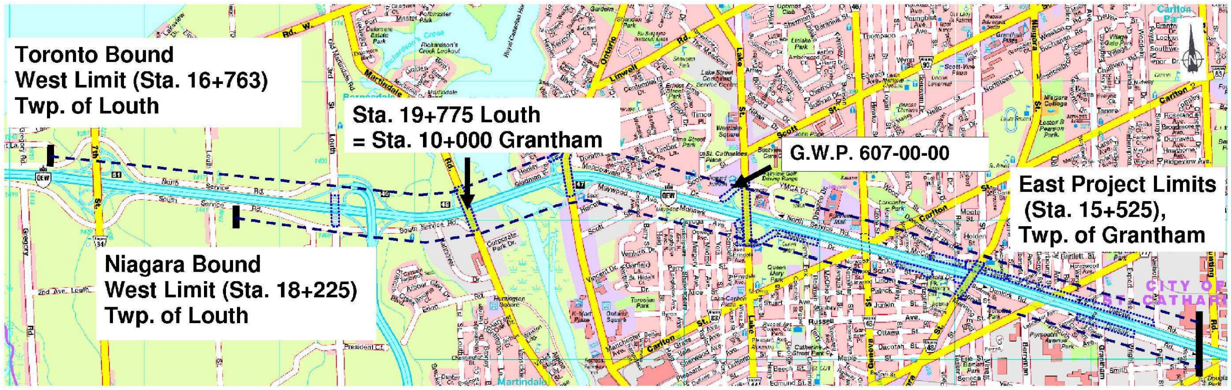

Figure 1 – Key Plan Project Limited (Reference MapArt Ontario)

In general terms, the project involves the widening of the QEW from four to six lanes through St. Catharines from Highway 406 to west of the Garden City Skyway. It also includes the rehabilitation of the existing pavement, construction of a median tall wall barrier and new storm drainage system, interchange and operational improvements, the rehabilitation/widening/replacement of structures, installation of full illumination, and construction of noise barriers and retaining walls.

The fieldwork for the pavement design and infrastructure management component was undertaken in two stages. The fieldwork for the investigation consisted of a visual condition survey of the paved surfaces, soils investigation (over 1,200 boreholes), asphalt coring (over 150 Cores), a Falling Weight Deflectometer (FWD) survey (over 600 locations), and a Ground Penetrating Radar (GPR) survey (over 120 km of coverage).

Figure 2 – The QEW Highway (Circa 1930s and 2004)

The visual condition survey provided information on the performance of the existing pavement conditions but could only provide indications of possible subsurface conditions based on surface expression of the pavements (such as surface cracks). The soil investigation, asphalt coring, and FWD data provided valuable information on the conditions at specific point locations within the project limits,. However, this requires that estimates be made of pavement and subsurface conditions between borehole, coring, and FWD test locations. For simplicity, these test types are referred to in the remainder of this paper as point source tests.

The GPR data were calibrated and interpreted in conjunction with the point source data, to provide accurate data between point source locations on pavement thickness, location of changes in pavements, and localized anomalies.

VISUAL PAVEMENT CONDITION SURVEY

A visual pavement condition survey was undertaken by two senior pavement specialists. The visual condition survey consisted of noting significant distresses and deterioration of the pavement on the existing lanes and shoulders, along with any distresses on the curbs, gutters and catch basins.

Generally, the pavement was found to be performing well, given its age and the growth in heavy commercial traffic in the previous twenty years. The main distress features identified included cracks, potholes, transverse and longitudinal cracks, and hot and cold mix patches. The paved shoulders were in relatively good condition; however the roadside ditching was no longer functioning properly in some areas. In addition, settlement of curbs and gutters due to washout of the underlying granular materials was noted at some locations. The overall condition and typical distresses within the project limits are shown on Figure 3.

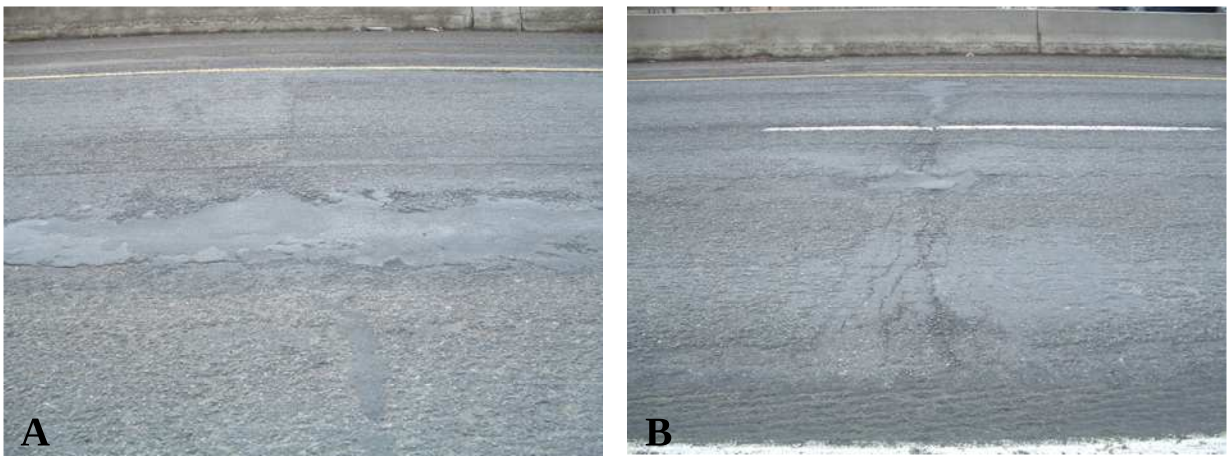

Figure 3 – Examples of QEW Condition: A) Patching of Lane 2, B) Moderate Transverse Cracking

BOREHOLE INVESTIGATION

Boreholes were advanced at selected locations along the QEW, at the edge of pavement, within the shoulders and along the ditchline, generally to a depth of 1.5 m except in the median shoulder where the boreholes were advanced to a depth of about 3.5 m. A total of about 730 boreholes were advanced along the QEW, as follows:

LOCATION	MEDIAN SHOULDER	MEDIAN LANE	OUTER LANE	OUTER SHOULDER	DITCH	TOTAL
Niagara-bound	34	34	76	125	65	**334**
Toronto-bound	44	41	85	151	78	**399**
Total	**78**	**75**	**161**	**276**	**143**	**733**

Boreholes were also advanced at selected locations along ramps and side roads, generally to a depth of 1.5 to 2.0 m. Over 440 boreholes were advanced for the geotechnical investigation of the ramps and side roads. The subsurface stratigraphy and groundwater conditions encountered in the boreholes were logged in accordance with MTO soil classification procedures. Representative samples of the various soils encountered were collected and were brought to a CCIL and CSA certified laboratory for further examination and laboratory testing.

COREHOLE INVESTIGATION

In conjunction with the soils investigation program, a pavement coring program was undertaken on the main lanes of the QEW to determine the thickness of the asphalt layers and the underlying Portland cement concrete (PCC) base, referred to as concrete for the remainder of the paper. A few cores were also obtained from the existing ramps and side roads. A total of 118 full-depth cores were obtained, 110 from the mainlanes on the QEW and 8 from the ramps and side roads.

All cores were either 100 mm or 150 mm in nominal diameter and were obtained using a portable, water cooled coring machine. The core samples were logged in the field and brought to a CCIL and CSA certified laboratory for further examination and compressive strength/petrographic analysis testing on selected samples.

The following table presents a summary of the asphalt and concrete thickness on the main lanes of the QEW as obtained from the cores.

PAVEMENT THICKNESS FROM CORES (mm)					
COMPONENT		ASPHALT / CONCRETE* THICKNESS (mm)			
		NIAGARA BOUND		TORONTO BOUND	
		LANE 2	LANE 1	LANE 1	LANE 2
ASPHALT	Range	190 – 480	150 – 420	175 – 520	200 – 380
	Average	260	260	250	230
CONCRETE*	Range	170 – 240	170 – 240	60 – 270	200 – 280
	Average	210	220	230	240

* Concrete where present.

Typical core samples from the QEW is shown in Figure 4. It should be noted that some of the cores were delaminated either at the interface of the asphalt layers or between the asphalt and the concrete.

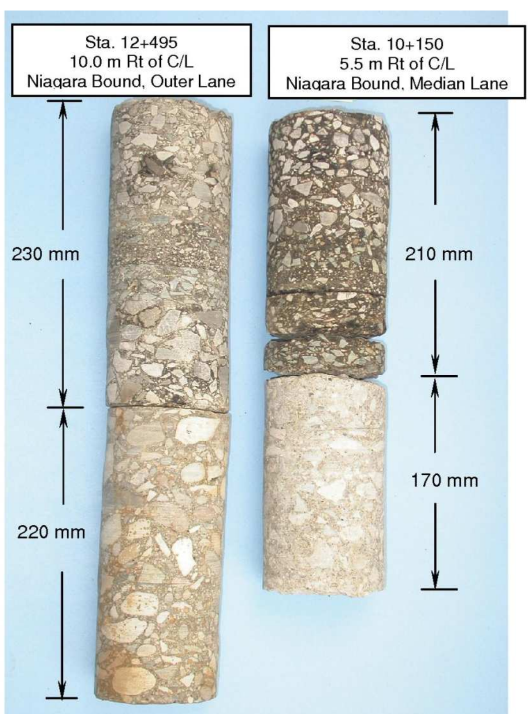

Figure 4 – Typical Core samples from the QEW

FALLING WEIGHT DEFLECTOMETER INVESTIGATION

The FWD load/deflection testing in the first stage was initially carried out to evaluate the structural condition of the pavement. The FWD tests were generally carried out on Lanes 1 and 2 in both directions at a test spacing of 50 metres, with tests in adjacent lanes offset by 25 metres. In addition, deflection measurements were also carried out at a few severe cracks that were identified during the visual condition survey as possible reflection cracks from joints in the concrete base. The tests at these locations were carried out on both sides of the crack to determine the load transfer efficiency across the joints.

At each test location, three load levels (about 40 kN, 55 kN and 75 kN) were used to determine the deflection response of the pavement. The measured pavement deflections were normalized to represent the equivalent deflections for a standard wheel load of 40 kN at an asphalt pavement temperature of 21˚C. The resilient moduli for the pavement layers and subgrade were determined using ELMOD 5 software. The results of the FWD testing were analyzed using several procedures to determine the normalized dynamic deflection, modulus of subgrade reaction, the modulus of both the concrete and the asphalt layers, along with load transfer efficiency and loss of support analysis.

The pavement deflections measured with the FWD at specific distances from the load plate were used to determine the structural properties of the pavement and subgrade through a process known as back calculation. Back calculation uses analytical pavement response models to predict deflections based on a set of subgrade and pavement layer moduli that produce deflections that are very similar to those measured in the field.

After the pavement moduli were estimated, the results were checked to determine if they were within the range normally expected for the materials under investigation. The resilient modulus of the asphalt layer was typically about 3,500 MPa, which is considered to be good considering that the testing was carried out on a pavement surface that had been in service for over 10 years. The underlying concrete had an average resilient modulus of 11,000 MPa indicating that the concrete is generally in fair condition but is providing excellent support for the thick asphalt layer overlying the concrete. Several problematic zones were identified using the FWD, which were identified and retested to confirm results.

OVERVIEW OF GPR TECHNOLOGY

There has been a lot of misuse and overselling of GPR technology for pavement investigations, which has, unfortunately, negatively impacted the industry's willingness to adopt GPR as a tool in standard pavement investigations. In an attempt to clear the air and demystify the technology, and in the hope that some of those who have had negative experiences in the past using GPR will reconsider, we delve into a little more detail of GPR technology than otherwise necessary for the purposes of this paper. However it is not intended to be a comprehensive overview of GPR.

A typical GPR system consists of two antennae (transmitter and receiver) or a single antenna combination transmitter/receiver, a control console and a computer for real-time, graphic display and data recording. In profiling mode, the antennae, separated a fixed distance from each other, are moved along the survey line and readings are taken at discrete intervals. At each test location, pulses of radar frequency electromagnetic energy (in the megahertz range) are transmitted and reflections received from subsurface horizons. Subsurface reflections occur at horizons where there is an abrupt change in material dielectric permittivity, such as at the interface between asphalt and concrete, and between pavement and granular materials. The amplitude of received radar energy is recorded as a function of time, processed in real-time for display purposes, and the raw data recorded digitally for later processing and presentation.

The resolution and penetration of a GPR system is dependent on the centre frequency of its operation. Typically, antennas having a centre frequency between 250 and 3,100 MHz are used for pavement investigations. Lower frequency antennas penetrate deeper into the subsurface, but have less vertical resolution than do higher frequency antennas. The lower frequency systems are typically used to map depth of granular materials, whereas the higher frequency systems can be used to determine the number of asphalt overlays on a road surface.

Because GPR data is collected as amplitude versus time, a key aspect to interpretation of GPR data is to have control at one, preferably several locations, along the survey line to verify the time-depth conversion. Although it is generally reasonable to provide preliminary interpretations of collected data, it is necessary to confirm GPR interpretations with data from intrusive investigations such as coreholes or boreholes.

The GPR antennas, whether shielded or unshielded, tend to pick up spurious air wave reflections from objects at surface and in close proximity to the survey line such as light poles and overpasses. These air wave events are, in general, distinct in their shape and frequency content as observed on reflection profiles, and can usually be identified with confidence on the GPR sections during interpretation.

Interpreted correctly, GPR can provide a continuous profile of the pavement structure and valuable information such as: an estimate of asphalt pavement thickness; the extent, approximate thickness and general condition of underlying concrete pavement (where present); the potential presence of voids beneath the pavement; the presence of underground services; the condition of soils overlying culverts and confirmation of the presence of frost tapers at culverts; and in some cases, the thickness of the granular layer.

AIR LAUNCHED VERSUS GROUND COUPLED GPR SYSTEMS

The majority of the GPR systems for pavement investigations are air launched GPR systems. These are high frequency systems (greater than 1000 MHz, and typically 2000 to 3000 MHz) that are mounted on a vehicle at a distance of 0.5 to 1 metre above the pavement surface. The frequency of the system is fixed, and depth of investigation using air launched is typically less than 30 cm below ground surface. The main reasons for limitation of investigation depth is the significant reflection of transmitted energy from the interface between air and the top of pavement, and that higher frequency waves attenuate quickly in the subsurface, therefore the higher the frequency the less the depth of effective investigation.

Ground coupled GPR systems are commonplace in other engineering applications, such as determining depth to bedrock, where the desired depth of investigation is significantly greater than 30 cm. To achieve the desired depth of investigation, lower frequency systems (12.5 to 1000 MHz) are typically used, and the transmitter and receiver are coupled directly to the ground to ensure the transmitted signal avoids significant energy loss due the air/ground interface reflection. Ground coupled GPR systems provide a greater depth of investigation and data with typically better signal-to-noise ratios.

Due to the longer time window required to collect data from reflections deeper in the subsurface, ground coupled systems historically could not be run at similar speeds to air launched systems. It is only with recent technological advances to increase data acquisition speeds that ground coupled systems are increasingly being used for pavement investigations.

PROCESSING OF GPR DATA

With the widespread use of air launched GPR systems, that typically collect data at survey speeds of up to 100 km/h, geophysicists were then presented with a problem; an enormous volume of data and, often, a quick turn-around time required to provide results to the client. The solution was to generate automated software based event picking algorithms that automatically screened the data to identify reflective layers and, therefore, significantly decrease the processing time. These automated software algorithms generally do a good job for shallow depth of investigation, where materials are man-made, continuous and uniform in composition, and where GPR signal strength is high in relation to background noise levels, which is typical of pavement systems.

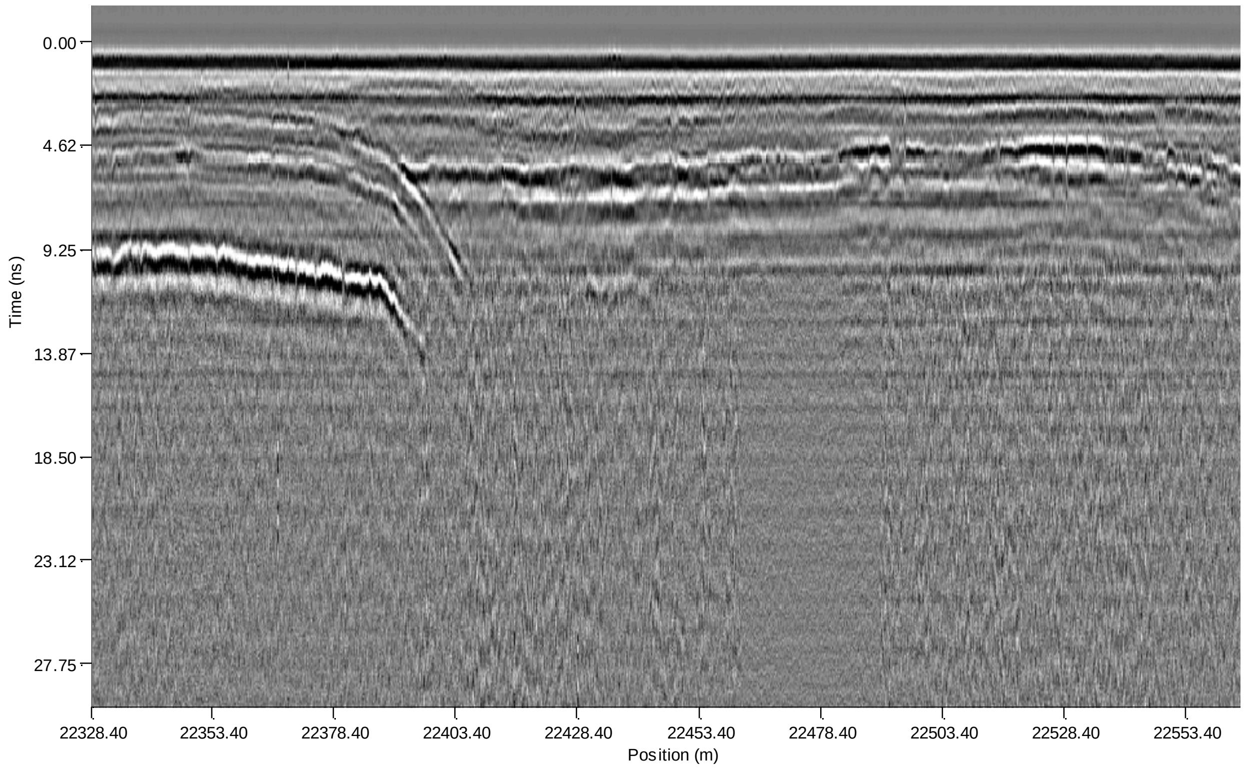

Figure 5 – Example of Raw Collected QEW GPR Data - Uninterpreted

The widespread availability of air launched GPR systems and automatic processing software allowed almost anybody with a little computer know-how to perform a GPR survey of pavement systems. The authors are aware of several pavement GPR surveys that have been completed where the results were provided without the aid of a single borehole or corehole to confirm the interpretation of the GPR data, only for the client to find out that the GPR data did not match the actual conditions when they intrusively investigated the pavements.

While the automatic layer picking software appears to have been labelled as the culprit in the preceding discussion, it is not. Data interpretation problems arise either because the data interpreter does not fully understand the GPR technology, to know that other means are almost always required to correlate the depth scale on a GPR section (such as coreholes), or because the different layers in the subsurface are misidentified due lack of understanding or knowledge of the tested pavement systems. To illustrate the point, we have provided an unlabelled raw GPR section of some of the data collected as part of the QEW project as Figure 5. There are evidently several reflectors present in the section. Without the advantage of additional information, such as coreholes or boreholes, it is difficult to interpret that this section illustrates a former level grade crossing, consisting of composite pavements with two asphalt overlays (approximately up to station 22+400) that has been replaced with an overpass with a pavement surface consisting of asphalt. It is also not possible to determine the depth to each layer. Please note that the scale on the left is in nanoseconds.

The authors recommend that GPR data be processed by someone with specific training in the processing of GPR data, preferably also with an understanding of pavement design. We recommend that automatic layer picking software be used sparingly, if at all, and then only to aid, not replace, data processing. The human element should not be removed from processing and interpretation of the GPR data, as it is necessary to make a proper interpretation of the data. It is always necessary to have some understanding of the pavement structure from means other than GPR to provide an accurate and meaningful interpretation of the GPR results and to estimate layer thicknesses. Following these guidelines will undoubtedly increase GPR survey costs, but at the advantage of providing the client data that correlates with point source data.

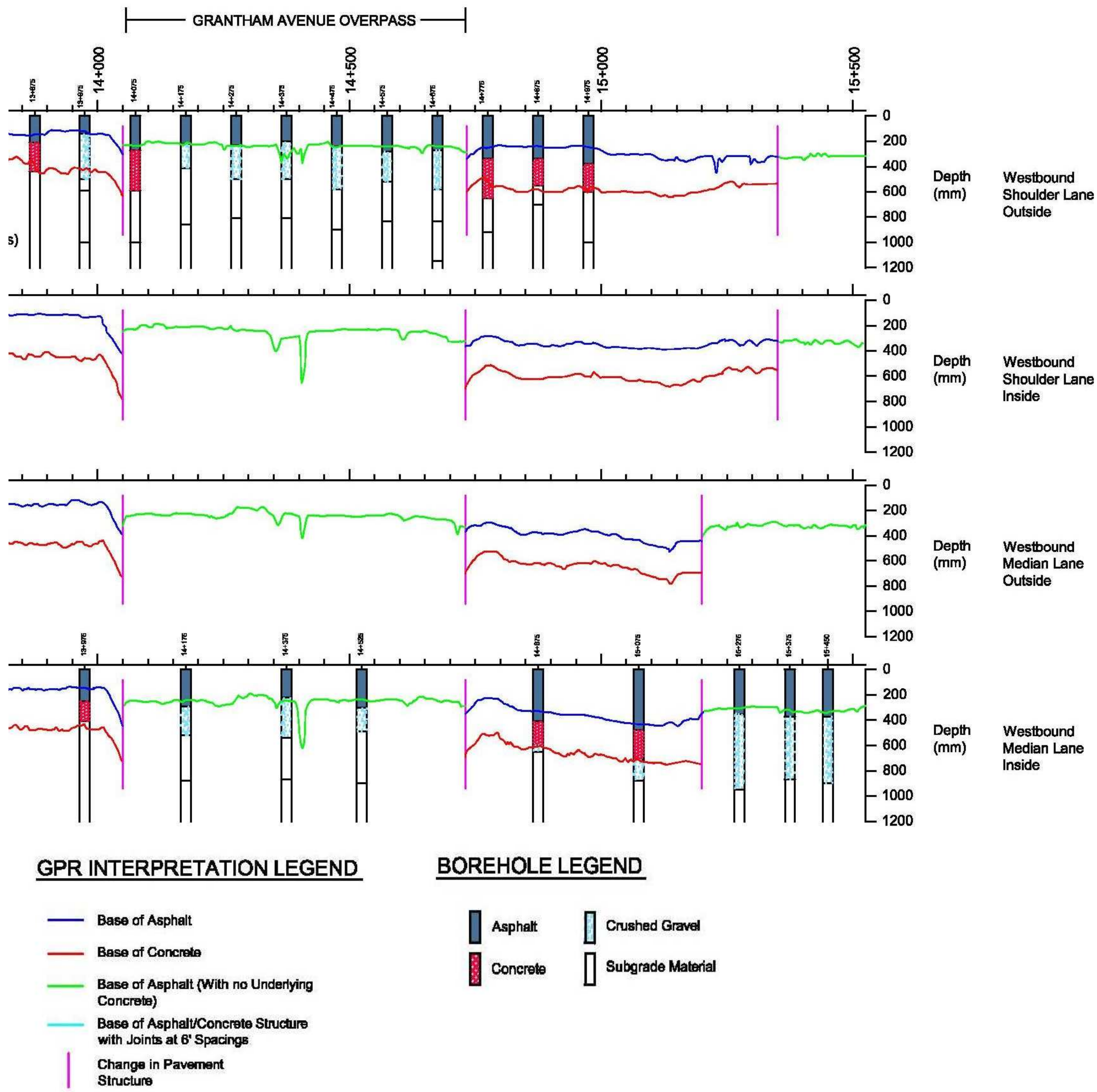

Figure 6 – Example of correlation between boreholes and GPR data for the QEW Project

GPR SURVEY OF THE QEW HIGHWAY

The objective of the GPR survey of the QEW Highway was primarily to identify the extent of composite pavements (asphalt-concrete pavements) within the project boundaries. Of secondary importance was to identify any localized anomalous zones indicative of deterioration of the pavement structure or of voids forming beneath and around joints in the underlying concrete. To accomplish this goal two ground-coupled GPR systems were utilised, a 1000 MHz and a 500 MHz system. The systems were run simultaneously and data were collected at 0.1 metre increments along the roadway, with a total of two passes per lane, one in each wheel path. Data acquisition speed was approximately 30 km/h, which allowed for rolling lane. Survey location was tied into both chainage markers along the roadway and to a differential GPS system which simultaneously logged data. Over two evenings, approximately 275 km of GPR data were collected, between the two systems.

Data were analyzed by a geophysicist with experience in processing GPR data, without the aid of automatic layer picking algorithms, and the average GPR velocity and pavement layers were identified through correlation to the borehole and corehole test results. The GPR data showed excellent agreement to the depths determined for boreholes and coreholes collected in the vicinity of the GPR data, as illustrated in Figure 6. Note that the borehole in the westbound shoulder lane at approximately station 13+970 was drilled in the shoulder, and therefore does not correlate with the GPR data.

Figure 6 clearly illustrates the benefits of using GPR in conjunction with conventional pavement investigation methods. The data clearly shows a difference in the extent of composite pavements between lanes near the eastern project boundary. Composite pavements end at approximately station 15+200 m in the median lane but continue until approximately station 15+350 m in the shoulder lane. The example in Figure 6 also illustrates a former level crossing, consisting of composite pavement that has been replaced by an overpass with asphalt pavement.

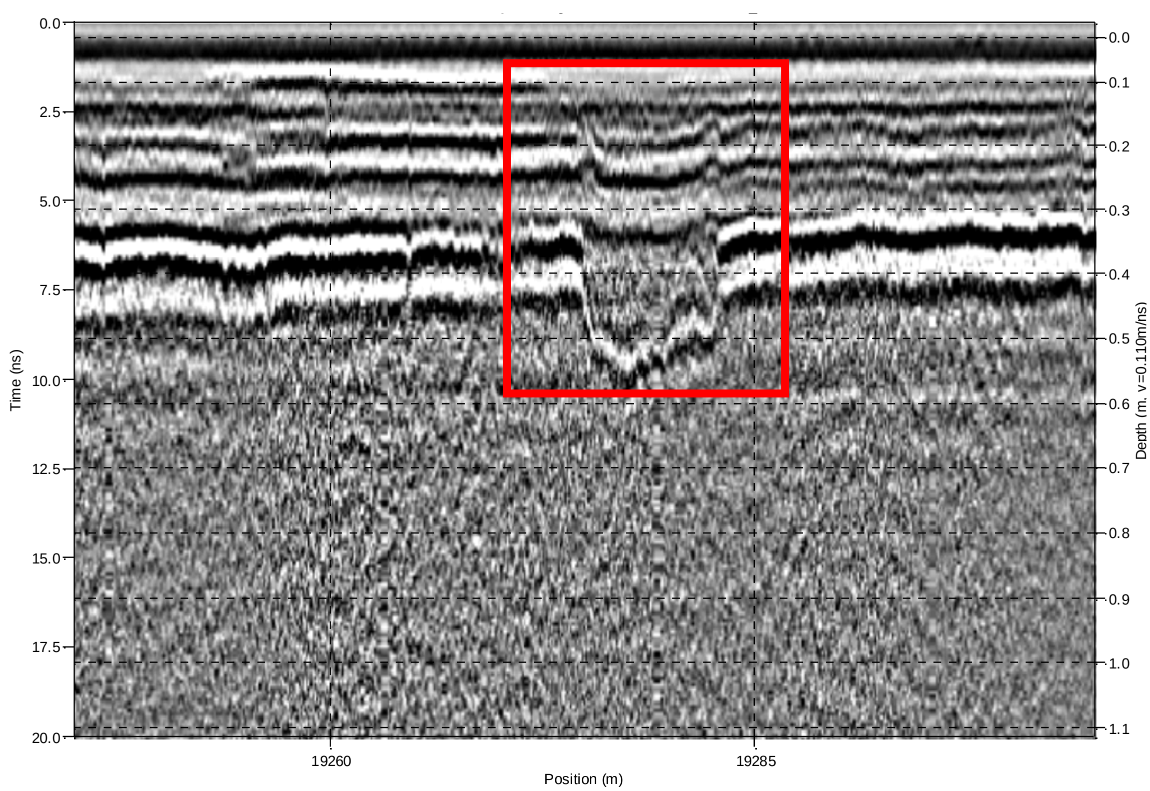

Figure 7 – Example of full depth asphalt repair of a failed concrete slab

The location of localized anomalies is another way in which the GPR results greatly aid a pavement investigation program. Figure 7 shows an anomaly in composite pavements in the eastbound shoulder lane of the QEW. The width of the anomaly is approximately 10 metres wide. There was no borehole at this location and the visual condition inspection noted two transverse cracks at the edges of the anomaly. Close inspection of the GPR data, however indicates that it is probably a failed concrete slab that has been replaced with a full depth asphalt repair. This possible repair may have been done prior to the last resurfacing of the highway, which could account for why the surface overlay showed no signs of an asphalt patch, with the exception of two transverse cracks.

Figure 8 shows the GPR results summarized in plan view for a small portion of the project. It shows the distribution of composite pavements beneath the lanes and shoulders, and shows that it varies even within the lanes. This is because of a change in road alignment. The median between the eastbound and westbound lanes increased slightly in this area in the original road alignment. The GPR was able to accurately identify the extent of composite materials.

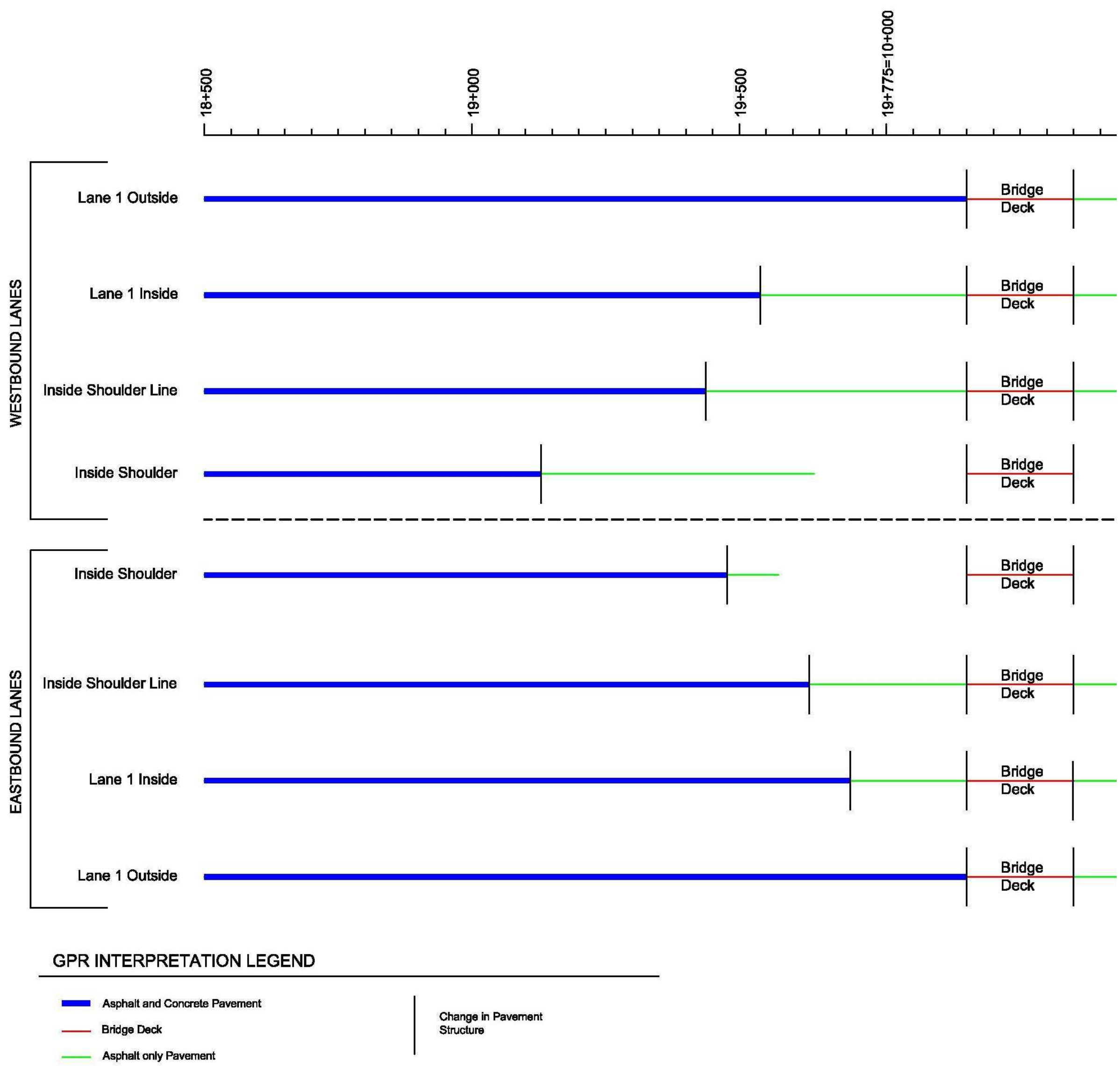

Figure 8 – Plan summary of GPR results for a portion of the QEW identifying an historical change in highway alignment (Blue is for composite pavements and Green is for flexible pavements)

Figure 9 shows a correlation between GPR results and FWD resilient modulus results for layer 2 (concrete when present, granular materials otherwise). The FWD interpretation integrated the GPR results by using GPR obtained layer thicknesses for the FWD test locations, which has been demonstrated to provide more accurate results than using the average layer thicknesses for the different pavement sections, which is the standard approach in the absence of GPR data (Hartman et al., 2004).

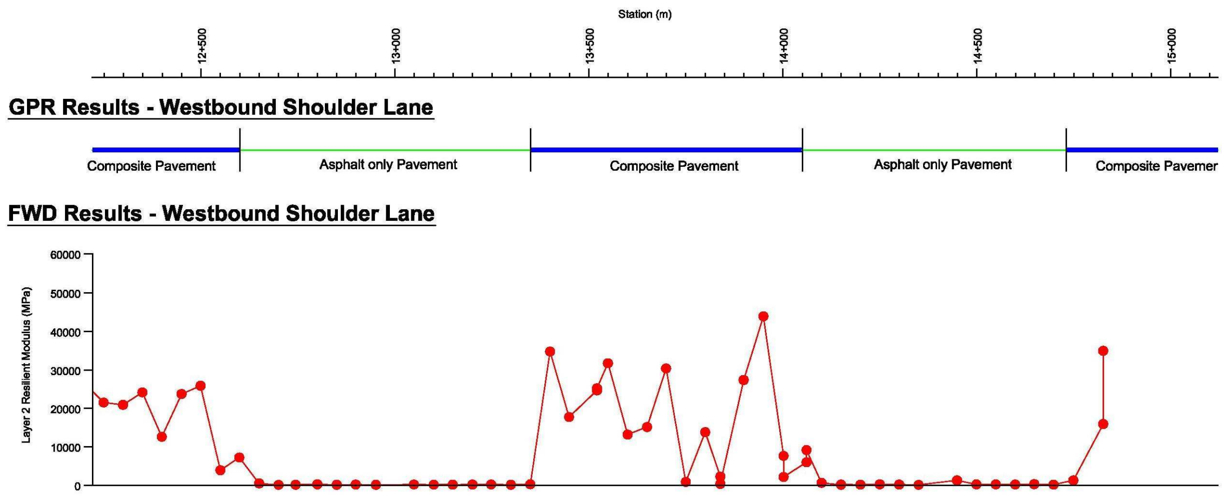

Figure 9 – Comparison of GPR and FWD results for the QEW Westbound Shoulder Lane

CONCLUSION

The use of GPR to complement conventional pavement investigation methods has been discussed in this paper. Through a case study, the integration of the GPR with conventional investigation methods has been demonstrated. GPR can increase the level of accuracy of a pavement investigation, and fill in the gaps between point source investigation tools, such as boreholes, coreholes, and FWD testing. GPR identified the precise location changes in the pavement structure, which could be difficult to achieve with other methods. The necessity of other means, such as borehole and corehole information, to calibrate the GPR data and interpret subsurface layering was discussed.

The results presented in Figure 6 indicate that with good quality GPR data it would be possible to reduce the amount of boreholes and coreholes required for a specific project, thereby decreasing overall project costs.

Through analysis of the GPR data in conjunction with the visual pavement condition inspection, several localized anomalies were identified, including the stepping of concrete slabs, full depth asphalt repairs, patches, and settlement due to underground utility corridors. The visual pavement condition inspection provided valuable clues which led to the detailed analysis of certain areas of the GPR data.

The GPR can provide detailed layer thickness information which can be used to refine falling weight deflectometer model data to provide an increased accuracy in FWD results where layer thickness is variable.

This paper, through its many examples of actual results, has shown how GPR, when interpreted and utilised properly, can dramatically increase what is known about the pavement system being investigated. GPR cannot replace conventional pavement investigation methods. Rather, it should be considered as a useful tool for pavement engineers, to aid in providing them with the information they need to make improved and sound engineering decisions on pavement design and rehabilitation.

REFERENCES

Ahmed, Z., Ahmed, R., and Helali, K. (2004). Evaluation of Ground Penetrating Radar Technology and Its Application in Pavement Management Systems. 5^{th} Transportation Specialty Conference of the Canadian Society of Civil Engineering, Saskatoon, Saskatechwan, June 2004.

Hartman, A.M, Baston-Pitt, J., Sedgewick, A., and Bohmer, G. (2004). Pilot Study Assessing the Feasibility of Advanced Ground Penetrating Radar in Pavement Assessment. Proceedings of the 8^{th} Conference on Asphalt Pavements for Southern Africa (CAPSA'04), September 2004.

Shang, J.Q., Umana, J.A., Bartlett, F.M, and Rossiter, J.R (1999). Measurement of Complex Permittivity of Asphalt Pavement Materials. Journal of Transportation Engineering., Volume 125, Issue 4, pp. 347-356, July/August 1999.

Uzarowski, L., Maher, M., and Balasundaram, A. (2005). Practical Application of GPR to Supplement Data from FWD for Quick Pavement Performance Prediction. 2005 Annual Conference of the Transportation Association of Canada, Calgary, Alberta, 2005.