Instrumentation monitoring of clay subgrade along southern Manitoba highways

David Kurz, Ph.D., P.Eng., Dami Adedapo, Ph.D., P.Eng., and
Rob Kenyon, Ph.D., P.Eng.
KGS Group, Winnipeg, Manitoba, Canada
Jeff Tallin, M.Sc., P.Eng.
Manitoba Infrastructure, Winnipeg, Manitoba Canada

ABSTRACT
A problem with structural deterioration was noted on a recently constructed flexible pavement highway founded on high plasticity glacio-lacustrine clays approximately 10 km south of Winnipeg, Manitoba. Various cracking was observed, including longitudinal, centerline, transverse, and some short random cracks. Primary hypotheses for the failure mechanism included swelling of the subgrade and differential frost action. Two highway sections of similar design were selected for instrumentation, focusing on monitoring soil moisture, ground temperature, frost action, and soil suction potential at the sites to determine factors that may have resulted in the observed distress of the pavement structure. Data for the two sites were collected from the two sites between November 2007 and November 2015. This paper presents and discusses the eight (8) years of field data that has been collected at the instrumented sites.

RÉSUMÉ
Un problème de détérioration de la structure a été noté sur une chaussée de chaussée souple construite récemment, construite à partir d'argiles glacio-lacustres à haute plasticité, à environ 10 km au sud de Winnipeg, au Manitoba. Diverses fissures ont été observées, notamment longitudinales, axiales, transversales et quelques courtes fissures aléatoires. Les hypothèses primaires pour le mécanisme de défaillance comprenaient le gonflement de la sous-couche et l'action différentielle du gel. Deux sections d'autoroute de conception similaire ont été choisies pour l'instrumentation, en se concentrant sur la surveillance de l'humidité du sol, la température du sol, l'action du gel et le potentiel d'aspiration du sol sur les sites afin de déterminer les facteurs de détresse observés. Les données pour les deux sites ont été recueillies sur les deux sites entre novembre 2007 et novembre 2015. Cet article présente et discute les huit (8) années de données sur le terrain qui ont été recueillies sur les sites instrumentés.

1 INTRODUCTION

Manitoba Infrastructure (MI) identified an early problem with structural deterioration of recently constructed flexible pavements founded on high plasticity glacio-lacustrine clays on Provincial Trunk Highway (PTH) 59 between the Red River Floodway, immediately south of Winnipeg, and Ile-des-Chênes, approximately 10.5 km south the Floodway (Figure 1). The granular base layers and the final bituminous surface was constructed in several phases between 2001 and 2008.

Cracking was noted in the late summer of 2004, nearly one year after paving was completed in October 2003. By the spring of 2005, cracks had widened and appeared to be top-down cracking suggesting upward flexure. Surface crack assessments completed by MI in October 2007 mapped the majority of cracking as C1 (Longitudinal in Wheel Path), C3 (Centreline), and C7 (Transverse). Short random cracks were also noted, mostly on or within 1.5 m of the shoulder. The longitudinal cracks, often up to 100 m in length or more, occurred most frequently from the middle of the passing lanes on the high side of the super-elevated curves in both the southbound and northbound directions. MI attributed the secondary transverse cracking to thermal strains in the asphalt structure under winter conditions. Overall, the observed cracks did not display features typically observed with fatigue. MI opted

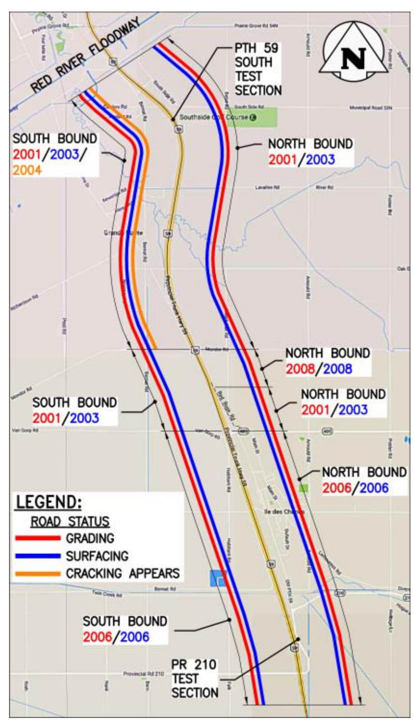

Figure 1. Site Location.

to investigate further to determine the cause of what was considered premature cracking.

1.1 Hypotheses of Mechanism

A comprehensive study by MI (2006) considered the following hypotheses as the mechanisms that led to the observed pavement distress:

(a) Swelling of the clay subgrade due to increasing in-situ moisture content
(b) Differential frost action
(c) Deficiency in the pavement material
(d) Deficiency in the structural design
(e) Construction sequence and methods

The MI study completed an investigation into the properties and structural adequacy of the pavement with falling weight deflectometer and thereby eliminated the hypotheses (c) to (e), concluding that the possibility of the observed pavement distress stemming from these failure mechanisms was remote. The construction records indicated as-built moisture contents were at or marginally dry of optimum but within specifications. While hypothesis (b) was originally eliminated too, some of the observed crack locations and crack patterns were consistent with similar patterns observed elsewhere, attributable to frost action and differential frost heaving as being a contributing hypothesis for the problem. Several publications written about deterioration of flexible pavements in cold climates identified differential frost action as a key mechanism for longitudinal cracking. Konrad and Roy (2000) discuss frost action being responsible for deformations both longitudinally and in cross-sections. In contrast, groundwater migration and subsequent swelling of unsaturated compacted high plasticity clay embankments is typically much slower and as such it is inconsistent with the speed at which failures developed at this site.

Regardless, the two hypotheses (a) and (b) are not necessarily exclusive or in direct contradiction. KGS Group was retained by MI in 2007 to assist with field instrumentation and assessment of field data to better understand both hypotheses. This paper presents a summary of selected data collected between November 2007 and November 2015. Data collection over this duration was completed to observe long term trends in the data to better understand the various measurements and to offset some anomalous readings after instrumentation installation, discussed further in following sections.

2 DESCRIPTION OF TEST SECTIONS

Two test sections were selected and instrumented on PTH 59 and Provincial Road (PR) 210 for the project.

The test section on PTH 59 is located on a super-elevated curve along the southbound lanes near station 190+00. This test location is a good representation of pavement sections that have showed premature cracking. The pavement structure is a total of 800 mm thick, consisting of two layers of bituminous pavement totalling 150 mm and two layers of crushed limestone base course totalling 650 mm on the highly plastic clay subgrade. The pavement containing the section received a micro-surface treatment in the summer of 2015 to maintain trafficability.

The pavement structure at the test section on PR 210 is thinner than on PTH 59 and showed premature cracking as well. The pavement structure is a total of 550 mm thick, consisting of two layers of bituminous pavement totalling 150 mm and two layers of crushed limestone base course totalling 400 mm on the highly plastic clay subgrade.

Schematic drawings showing the pavement section and details of the instruments installed on PR 210 and PTH 59 are shown in Figure 2(a) and (b), respectively. These figures also show maximum measured frost depths as discussed in Section 4.0. Ditching occurs on either side of the roads and the embankments are elevated a

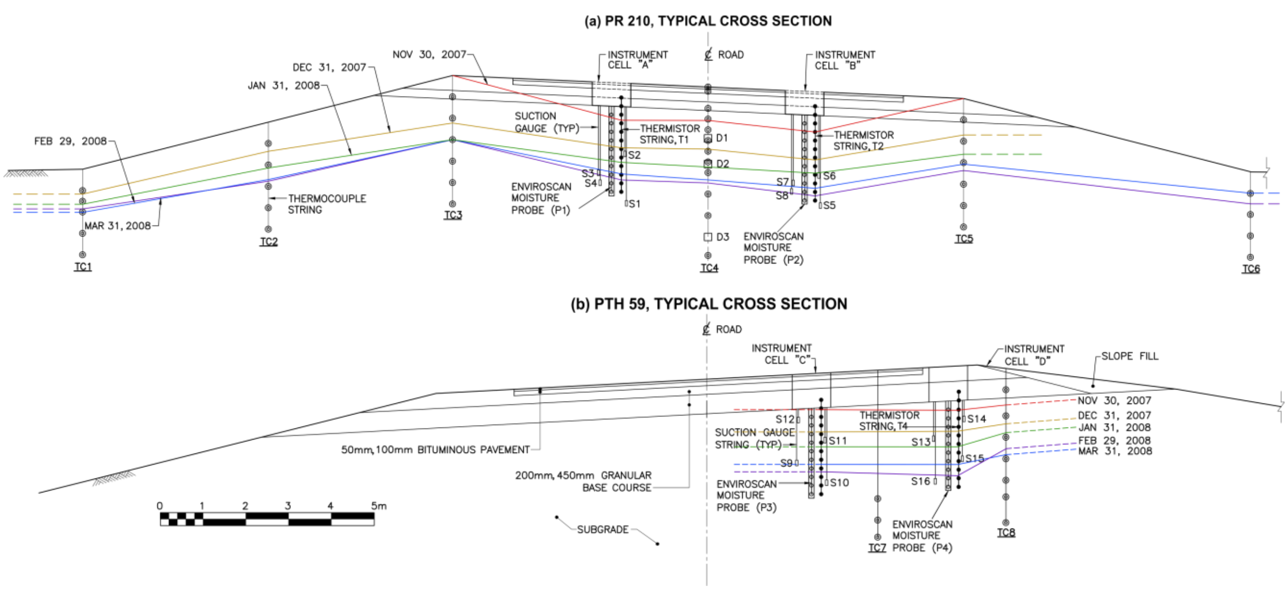

Figure 2. (a) PR 210 Cross Section, and (b) PTH 59 Cross Section.

few metres over native prairie elevations. Adjacent land is primarily agricultural.

3 INSTRUMENTATION OF TEST SECTIONS

A total of sixty-seven (67) and ninety-eight (98) sensors were initially installed within the pavement test sections on PTH 59 and PR 210, respectively to measure volumetric water content, ground temperature profile, air temperature, frost depth, suction gradient and liquid (rainfall) precipitation. The following sensors were installed at each test sites:

- 20 EnviroSCAN moisture content sensors
- 24 RST thermistor sensors,
- 2 Time Domain Reflectometer (TDR) probes
- 8 Watermark Suction gauges/ Tensiometers
- 1 Rain gauge
- 1 Frost depth gauge (PR 210)

Subsequently, an additional, 10 and 38 thermocouple units, were installed on PTH 59 and PR 210, respectively. Five (5) thermocouples installed at PR 210 did not function post-installation. Three (3) frost heave gauges, discussed in Section 4.4, were installed on PR 210 to measure ground deformation due to frost action in the centerline of the roadway. Data was collected by an on-site data logger for each test section, complete with solar panel and battery back-up. The spatial arrangement and identification of the sensors within the pavement structures are shown in Figure 2(a) and (b), respectively.

4 MONITORING DATA

Data collected by both KGS Group and MI during the study was compiled by KGS Group. Data is referenced as depth below ground surface for each instrument.

Generally, the quality of the data obtained from the instruments was good. There were, however, anomalous readings that may have indicated instrument malfunction or conditions beyond the range of the instrument. Possible sources of instrument error include: loss of contact between the soil and sensor, moisture infiltrating the sensor, and electrical issues (i.e. a loose wire or a short circuit). These possible factors are not discussed further in this paper. The plots herein may illustrate gaps where malfunctions were determined and data was either omitted or null values were collected.

Overall, there are similar trends in the instrument readings for both the PR 210 and PTH 59 sites. The following sections discuss the data.

4.1 Temperature Measurements

Overall, the ground temperature data provides insight into the change in the thermal regime at the two test sites and may be used to correlate behavior in the soil with respect to changing moisture, frost heave and soil suction. The zero degree (0°C) isotherms (depth of frost) provided insight into the maximum depth of frost and rate at which progression and recession of this isotherm occurred.

Figure 2(a) and (b) display the frost depths achieved monthly for the 2007-08 winter season for PR 210 and PTH 59, respectively. This also appears to have been the approximate maximum frost depth for all subsequent years where data was recorded. Overall, the average maximum frost depth beneath the paved section is approximately 2.3 m ±0.4 m for both sites. The depth of frost depends on the rate of temperature change and the amount of snow cover, among other factors. The depth of frost decreases towards the adjacent shoulders and ditches. This correlates with snow plowed from the roadway allowing frost below the pavement section to reach a greater depth than on the embankment slopes.

Figures 3 and 4 summarize the 2007 to 2015

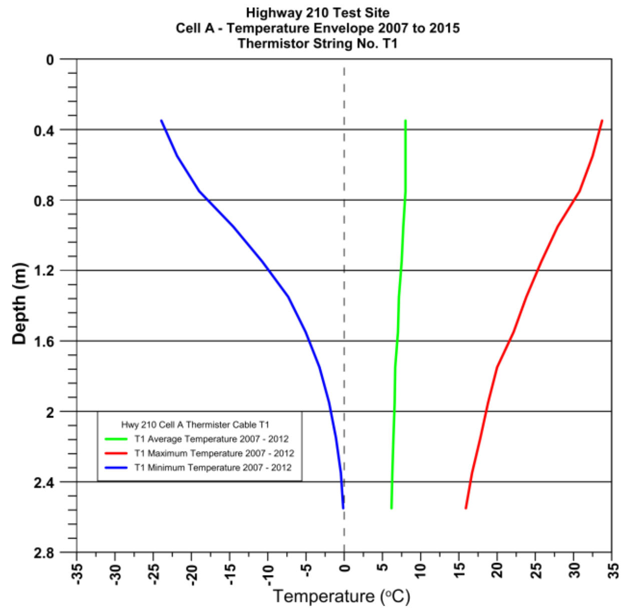

Figure 3. PR 210 - Temperature Envelope.

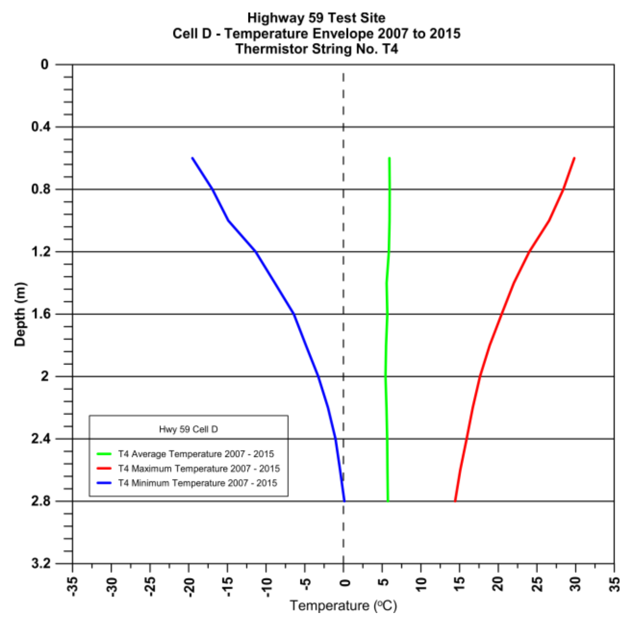

Figure 4. PTH 59 - Temperature Envelope.

minimum, maximum, and average temperature envelopes for selected thermistor strings at each site. The average yearly temperature profile displays a slightly positive inclination, indicating a slow warming trend overall.

4.2 Moisture Measurements in the Clay Subgrade

The EnviroScan moisture probes were installed below the Class “C” base in the clay subgrade at both sites. At PR 210, two (2) probes were installed (P1, Cell A and P2, Cell B), one in the centre of each lane. At PTH 59, the two (2) probes were installed in the centre of the passing lane (P3, Cell C), and the shoulder of the passing lane (P4, Cell D). At both sites, one probe performed admirably since installation (P1 and P4), whereas one probe experienced more malfunctions (e.g. interruptions in readings, erroneous readings, etc.) (P2 and P3). Figures 5 and 6 illustrate the more complete data set for PR 210 (P1) and PTH 59 (P4), respectively, and show the changes in volumetric moisture content for each sensor with time plotted with the zero degree isotherms. Depths indicated are measured from the pavement surface.

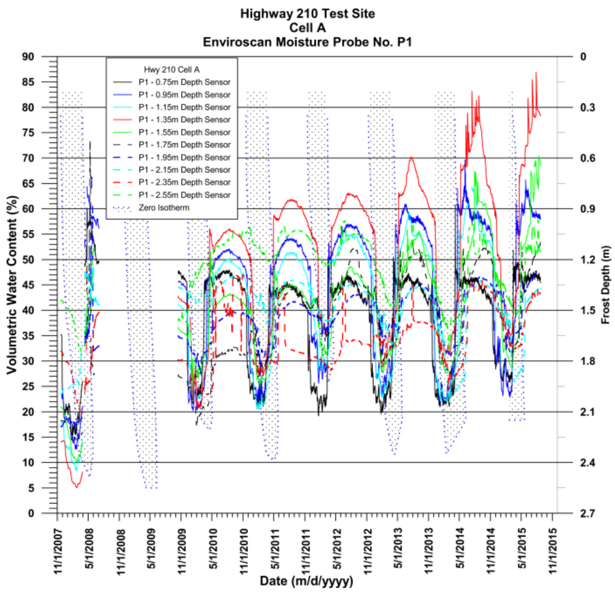

Figure 5. PR 210 - Moisture Probe Data.

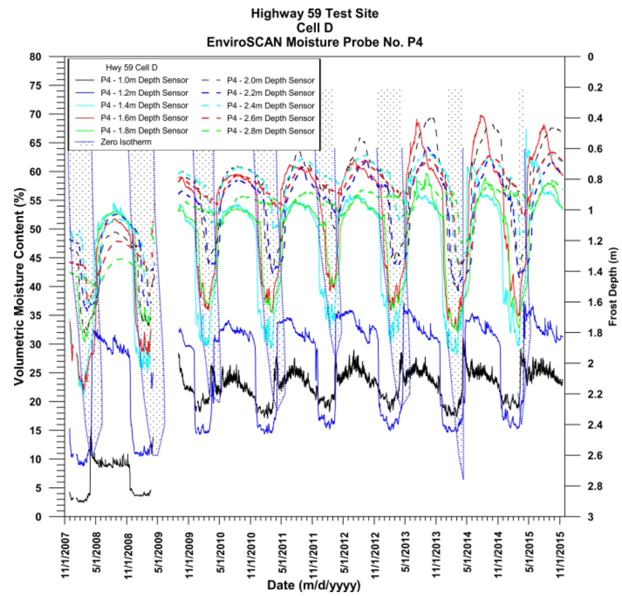

Figure 6. PTH 59 - Moisture Probe Data.

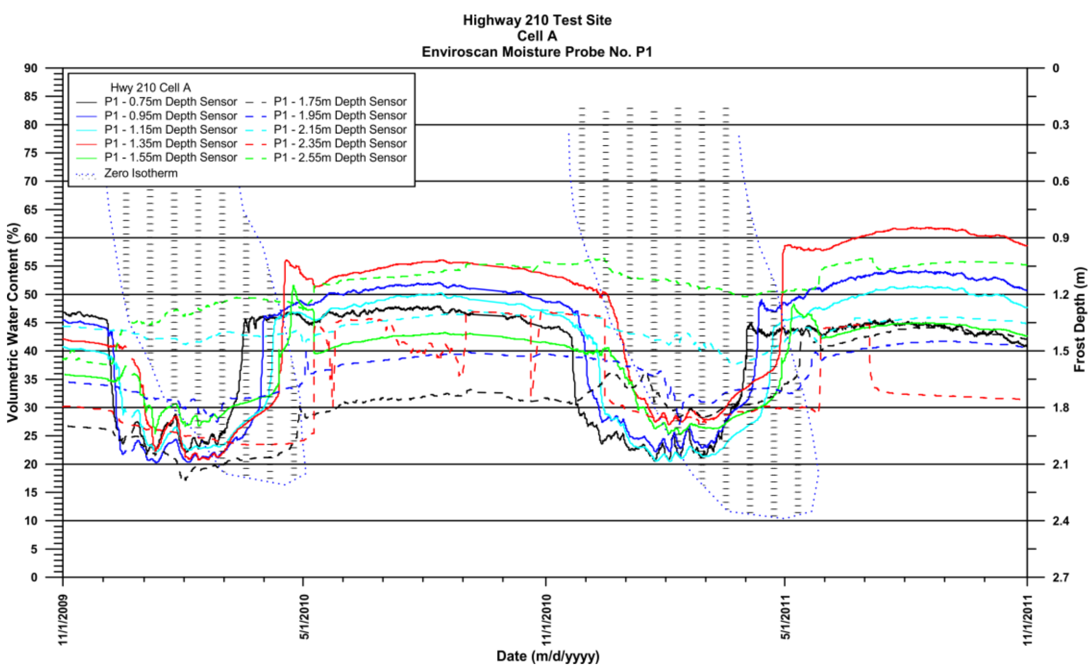

Figure 7. PR 210 - Moisture Probe Data, 2009-11.

The summary time series plot for EnviroScan Probe P1 (Figure 5) installed on the high side of the super-elevated curve illustrates a general trend of increasing volumetric moisture content with time, more obviously in the sensors within the compacted clay fill layer in the upper one metre (1 m) below the granular layers. This trend is visible to a lesser degree in Probe P2 (not shown here) installed on the low side of the super-elevated curve. Figure 7 illustrates typical annual cyclical behaviour for November 2009 to November 2011 for the same Probe P1. This figure shows rapid decreases in volumetric moisture content with the advance of the freezing front, followed by rapid increases in volumetric moisture content during spring thaw. These variations in moisture content are more noticeable within the upper one metre of the compacted clay fill layer. The gauges show reasonable correlation with increases and decreases in volumetric water content that begin with the shallowest gauges and end with the deepest gauges. This correlation reasonably coincides with the advancement of the freezing front and the thawing front in the fall and spring, respectively.

Figures 8 and 9 illustrate the November 2013 to November 2014 data for the gravimetric water content profile for moisture probe P1 and P4, respectively. This data shows that the approximate minimum/maximum moisture profile occurs in February and August, respectively, and represents approximately a six (6) month cycle. Included on this plot is the gravimetric water content profile of soil samples recovered during instrumentation installation obtained from laboratory testing for comparison. The figures show that gravimetric water contents measured in October 2007 during instrumentation installation (for TH2 and BH02) fall on the high side of the range of values subsequently measured. No distinct variations in the boreholes were noted to indicated reasons for the more differences in native moisture contents between the two test locations. The seasonal variation of moisture content is noticeably large in the upper one (1) metre of the sensors. Some of the measured water contents exceeded initial measurements at the time of instrumentation installation particularly in more recent years implying increase in water content of the clay. The large seasonal fluctuation in measured water content is also attributable to ground freezing and advancement of the freezing front during winter months.

These plots indicate that most moisture changes exist within the compacted clay fill layer immediately below the granular layers. The general trend of increased moisture content in the clay fill indicates a slight cumulative increase in moisture content on a yearly basis and potential swelling of the clay fill. The direction of moisture migration (i.e. vertical or lateral) cannot be ascertained other than the general knowledge that moisture migrates to the freezing front. The moisture probes, P1 and P2 or P3 and P4, by themselves do not lend much insight into evidence of lateral moisture movement from one side of the embankment prism to the other.

4.3 Soil Suction

Watermark suction gauges were installed below the granular base in the clay fill and native subgrade at both sites. At PR 210, eight (8) probes were installed, four (4) in the centre of each lane. At PTH 59, the eight (8) probes were installed, four (4) in the centre of the passing lane, and four (4) in the shoulder of the passing lane. Each gauge was installed at different depths between 1.0 to 2.7 m below the surface of the pavement. The gauges were anticipated to provide suction values to assist in

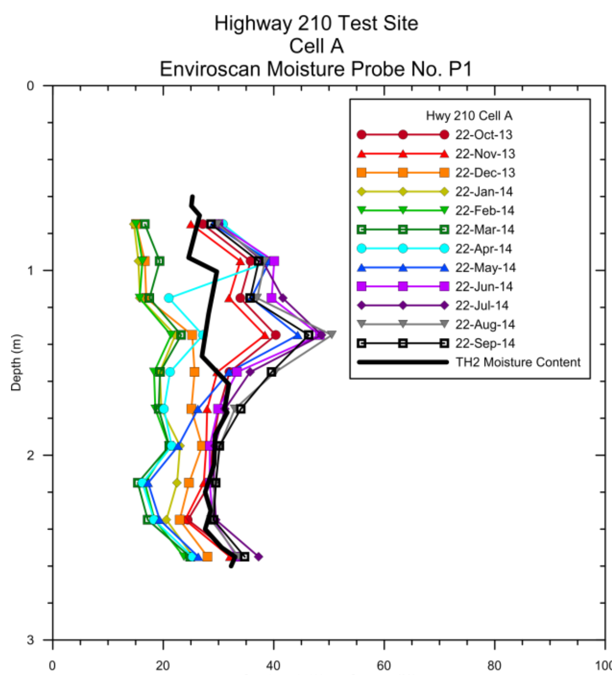

Figure 8. PR 210 - Gravimetric Water Content.

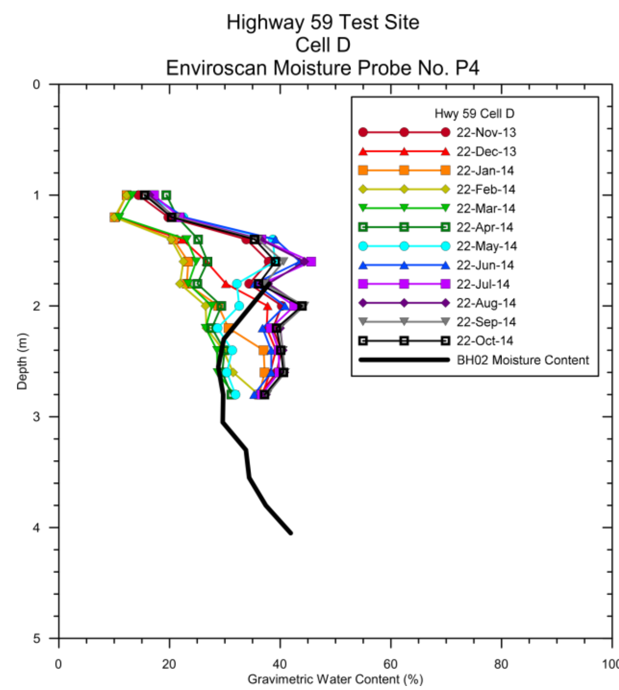

Figure 9. PTH 59 - Gravimetric Water Content.

correlating the advance of freezing front and the zone of moisture migration within the cohesive subgrade material.

Figure 10 shows a logarithmic plot for the cluster of suction gauges in Cell A at PR 210 compared to the zero degree isotherms. The plot typically shows higher suction values during frozen conditions compared to the thawed conditions. Cell A generally indicates higher suction values in the shallower gauges, S2 and S3, compared to the deeper gauges, S1 and S4, implying upward migration of water. Cell B does not display the same trend (Figure 11). Similar data is observed in Cells C and D at PTH 59 but is not shown here.

Data often exceeded the working range (0 to 200 kPa) of the suction gauges. Formulae in the manufacturer's documentation and other publications (e.g. Allen 2000) to convert raw resistance (kOhms) to suction potential (kPa),

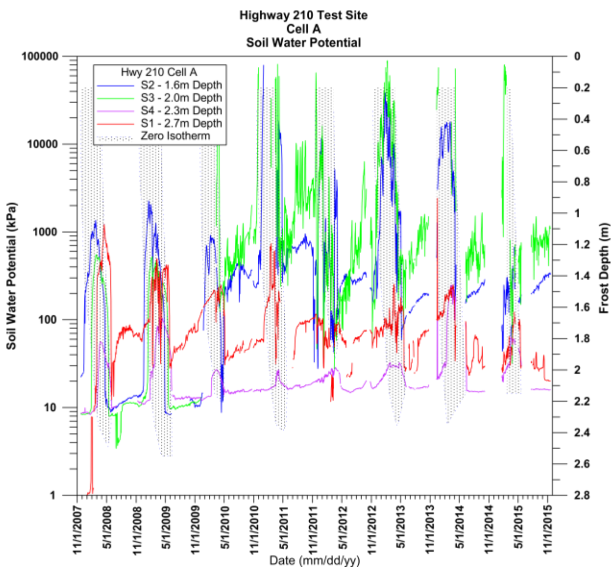

Figure 10. PR 210 - Suction Potential - Cell A.

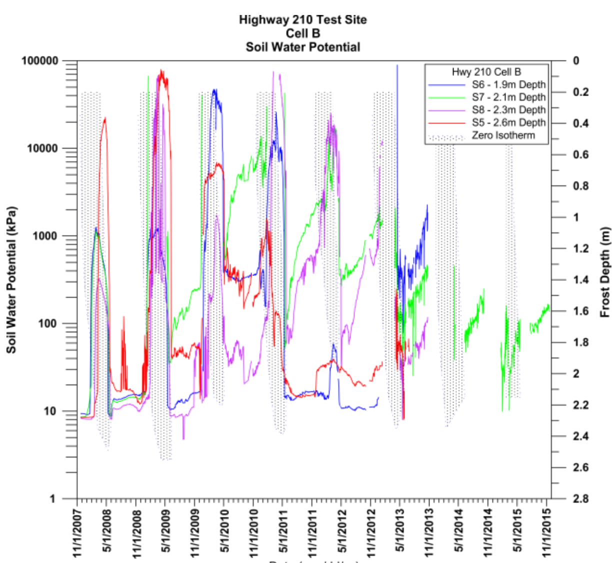

Figure 11. PR 210 - Suction Potential - Cell B.

originally developed for a clay loam, were noted to be limited for resistances exceeding their intended range. Specific calibration formulae for the clay found locally were not developed in this program. In addition, communication with the manufacturer and review of other reports (e.g. IAEA 2008), indicated that the gypsum filter stone may also become desaturated at high suction values (typically exceeding 600 kPa), although, the gauges often show decreases in suction pressure, often back under 600 kPa or less each spring. Suction values exceeding 600 kPa are possible in clay soils (e.g. Tu and Vanapalli 2016) but measuring these pressures, particularly in freezing environments, can be difficult and may be impacted by factors such as the rate of temperature change and available water.

In general, a comparison of the soil water potentials on the low side of the super-elevated roadway to the high side at approximately 2 m depth suggests a potential lateral flow of water from the high side to the low side. However, there are times that indicate reverse flow albeit at lower soil water potentials. Observations pertaining to trends in the data must use caution as measured values often exceed 200 kPa (working range of gauge).

4.4 Frost Heave Measurements

Extensometer gauges, as depicted in Figure 12 (a design by Dr. J.M. Konrad, Laval University), were installed in the centreline of PR 210 (D1 to D3 in Figure 2(a)) to provide frost heave data. The three gauges were secured to the pavement at the surface and anchored at three depths within the clay subgrade; 1.2 m, 1.8 m, and 3.5 m. The lengths of the extensometers at installation are considered the 'neutral' or zero readings. As the freezing front progresses through the road embankment, the extensometers are lifted and record upward (positive) movement. As the freezing front passes a depth of 1.2 m, the confidence in the first gauge is less as both anchor points are potentially moving upward, and differential movement may not be fully recorded. Similarly, confidence in the second gauge is less as the freezing front passes the anchor point at 1.8 m. Since the maximum depth of frost did not exceed approximately 2.3 ±0.4 m, the deepest gauge is expected to have experienced the maximum frost heave. The pavement surface is assumed to heave uniformly over the short lateral distance between gauges.

Figure 13 illustrates the frost heave data for PR 210 versus time with the zero degree isotherms overlain for comparative purposes. Data was not collected for PTH 59. The freezing front progresses fairly quickly through the granular base course material at the onset of winter. The depth of frost reaches 1.2 m on average between 10 and 15 days. During this period, the gauges all heave upwards relatively the same magnitude for a given year. After this period the gauges diverge with attenuated heave in the shallowest (first) gauge, follow by attenuated heave in the second gauge shortly after. The maximum overall heave is shown in the deepest extensometer, as expected, and ranges from approximately 10.5 mm to 27.5 mm and averages 17 mm (<3/4") annually. The maximum heave generally coincides within a few days of either maximum frost depth or just prior to the onset of thawing at the surface, consistent with the temperature profiles.

The differences between the gauges can be compared to evaluate differences in a layered system. Figure 14 illustrates the difference in heave between each gauge. The difference between the gauges at 1.2 m and 1.8 m is reasonably consistent at 1-2 mm, apart from the rapid increases as the freezing front passes the gauges suggesting the two gauges heave upward together once the freezing front passes 1.8 m. The differences between the 1.2 m to 3.5 m and 1.8 m to 3.5 m display a cumulative negative displacement between approximately 6 mm to 8.5 mm. Since the freezing front does not impact the anchor plate at 3.5 m (i.e. average frost depth at ±2.3 m) and assuming the pavement anchors heave uniformly, there is a decrease in the distance between the anchor plates at 1.2 m and 1.8 m to the plate at 3.5 m.

At the onset of thawing, each gauge measures a sharp drop in the heave down to near ‘zero’ values within one month indicating that frost heave is only seasonal and not cumulative upward movement. However, the ‘neutral’ points for all the frost gauges gradually progress downward (at different rates) with time for each gauge. The values are relatively small but the deepest gauge (3.5 m) now zeroes at approximately -8.5 mm. This downward shift in the ‘neutral’ point since 2012 may possibly be due to the settlement of the pavement structure resulting from the consolidation of the cohesive subgrade material or potential break in the connection to the pavement structure. In Winter 2014, the gauges began giving anomalous readings but the cause has not been investigated further.

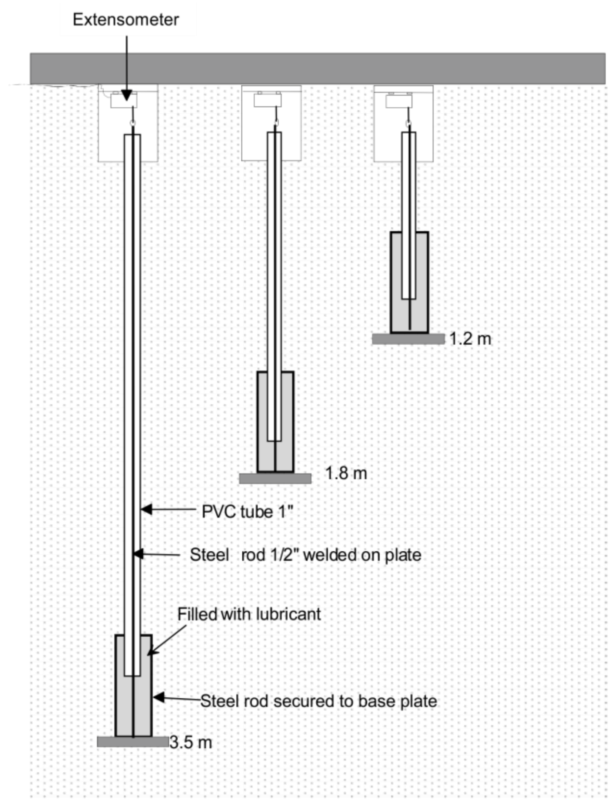

Figure 12. Frost Heave Gauge setup.

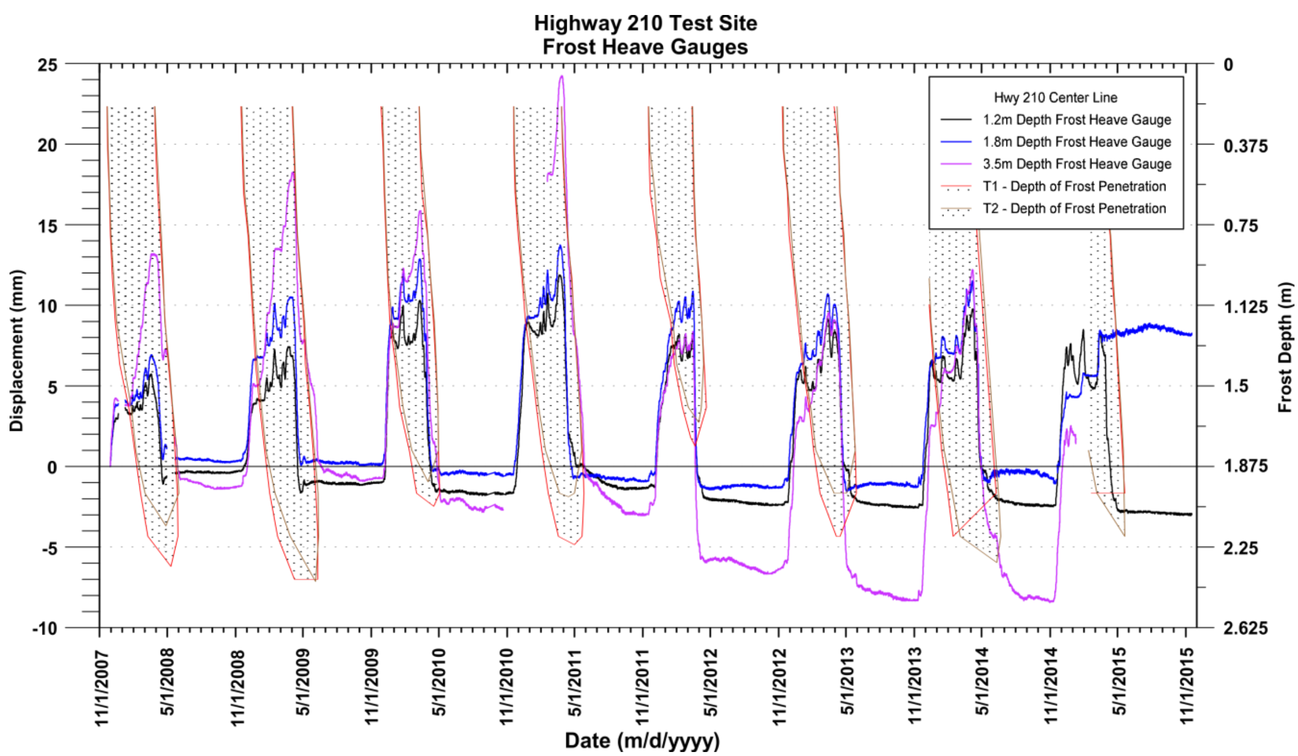

Figure 13. PR 210 - Frost Heave gauges.

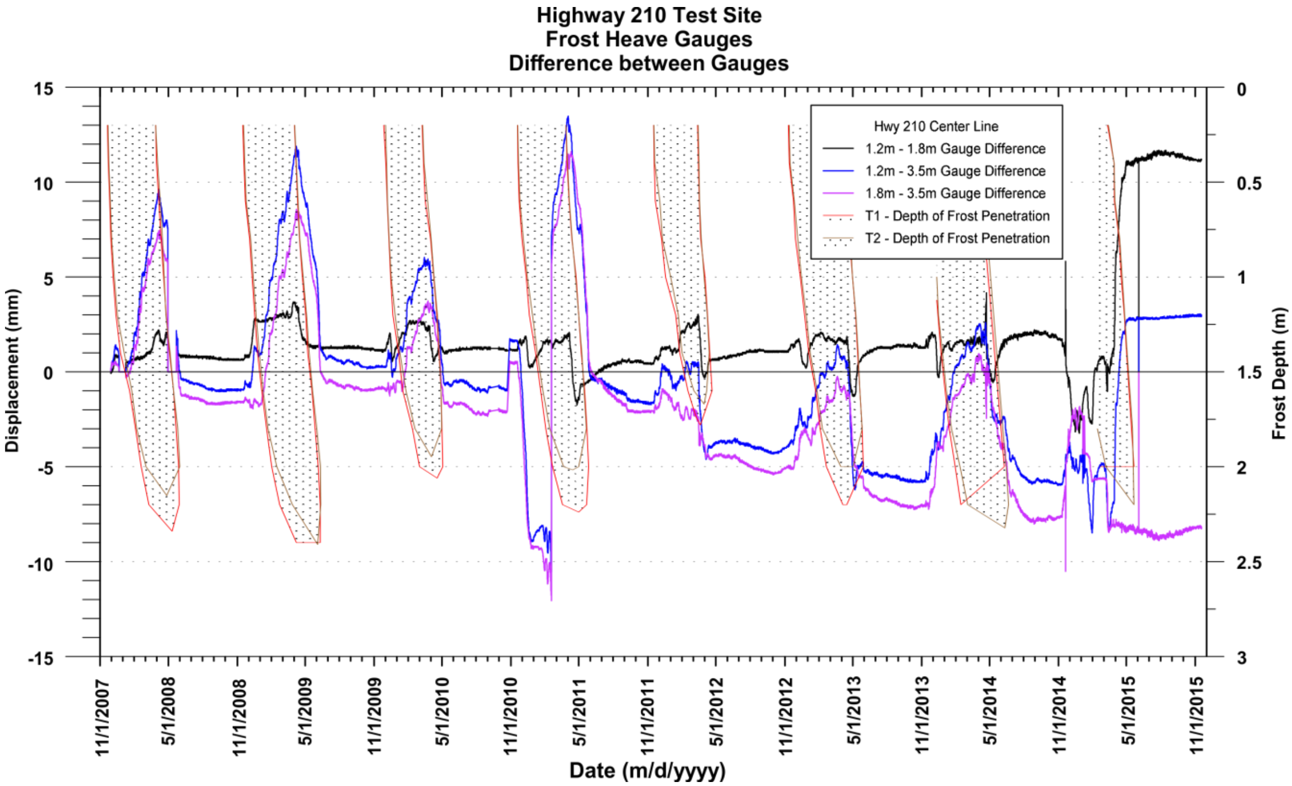

Figure 14. PR 210 - Differential movement in Frost heave gauges.

5 CONCLUSIONS

The instrumentation installed at the PR 210 and PTH 59 South sites provide valuable insight into the behavior of the embankment since monitoring began in 2007. The data from the different instruments, as discussed in Section 4.0, provides broad findings for temperature, moisture content, suction potential, and frost heave. Insight into the mechanics occurring at these sites can be gained when the instrument data is examined collectively.

The data suggests that the largest fluctuation of moisture occurs within the compacted clay fill and would lead to swelling in the expansive lacustrine clays found in Manitoba. There is also evidence of cyclical frost action occurring. The study completed by MI (2006) explored the type of cracking observed and provides insight in to the impact of swelling pressures and tensile microstrains on the pavement structure. It is estimated that heave, using the relationship in the MI report (2006), would lead to approximately 5 to 8 mm of heave. This is approximately half of the average frost heave (17 mm) measured at the PR 210 site between 2007 and 2015.

The field data indicates that the two hypotheses are not mutually exclusive. Konrad and Roy (2000) discuss similar phenomenon at sites in Quebec as observed on the sites in this project. Although a swelling clay leads to gradual uptake of water and heaving, frost action also contributes to increases in water, heaving, and consolidation. These aspects are observed in the data for the PTH 59 and PR 210 sites.

This paper has provided a snapshot of the of the data that has been collected over an eight (8) year period, and offers the opportunity to better understand the impact of moisture migration, frost action, and road construction on a clay subgrade in southern Manitoba. Currently, MI is not changing their construction specifications, but are exploring the merits of increasing the compaction moisture content to reduce volume change potential.

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