Calgary Airport Trail Tunnel Monitoring Program

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ABSTRACT

The Calgary Airport Trail Tunnel is a cut-and-cover, two-cell roadway tunnel constructed under the Calgary International Airport's runway and three associated taxiways. It is owned by The City of Calgary (The City) and is on land leased from the Calgary Airport Authority (YYC). The structure is a cast-in-place, conventionally reinforced concrete rigid frame on spread footings with two spans of 17 m each and a total length of 620 m. The Tunnel was designed according to the Canadian Highway Bridge Design Code (CHBDC)[1]. One of the load cases considered in the design was loading due to temperature effects (including temperature variations and thermal gradient). Based on the CHBDC [1], the design temperature range for Calgary is from -34 to 38°C. It was discussed during the design stage that the Tunnel, which is a buried structure, may not actually be subjected to this temperature range. The design team could not find any references that addressed temperature ranges inside tunnels.

Another issue raised during the design stage was the necessity for movement joints. Although some references recommend joints as close as 9 m apart, there are tunnels that have been constructed without any joints. To investigate these questions for future designs, it was discussed with The City and it was agreed to put temperature and movement monitors in the tunnel. Wireless sensors were cast into the concrete walls and roof slab at 40 locations to measure temperatures at two surfaces and the mid-depth of each section. Also, surface mounted sensors were installed at two movement joints to monitor the tunnel's movements.

After providing a summary of the Tunnel and monitoring design, the paper emphasizes the findings from the monitoring program, including:

- Average maximum and minimum temperatures and thermal gradients recorded inside the Tunnel
- Comparisons with temperatures recorded outside the Tunnel at the Calgary Airport
- Comparisons to the design temperature range and gradient provided by CHBDC [1]
- Results obtained from movement sensors.

1 – INTRODUCTION

The Calgary International Airport (YYC) undertook the Airport Development Program to allow the world's largest aircrafts to land at the airport and facilitate an increase in international air traffic to Calgary. The program involved the construction of a new 4,260-metre (m)-long runway and associated taxiways, as well as a new International Terminal and associated support buildings. Construction of the program necessitated the closure of some of the existing access roads to YYC. The Calgary Airport Trail Tunnel (Tunnel) was designed and constructed to provide a new eastern access for public vehicle traffic to the airport. The Tunnel also forms part of one of Calgary's main east- west connectors, with future connection planned to the Calgary Ring Road. The Tunnel was designed as a 620-m-long rigid frame concrete structure, with two cells and six lanes. It was constructed under the new runway, associated taxiways and services roads.

Design of the Tunnel was undertaken in accordance with the CAN/CSA S6-06 Canadian Highway Bridge Design Code (CHBDC) [1]. The requirements and design guidance provided in CHBDC [1] are mainly for bridge structures. Although a tunnel could be considered a special type of bridge, there are some aspects of these structures that are not the same.

One of the main questions considered during the design stage was the difference in temperature loading for bridges and tunnels. Tunnels are not exposed to different climatic elements such as sun and wind the same way that bridges are. In tunnels, one surface is always in thermal contact with soil (through a waterproofing membrane), and the other surface has limited atmospheric exposure through air circulation in the tunnel. The total temperature range as well as the temperature gradient across the thickness of a structure, could be different for a tunnel and a bridge in the same climate. The CHBDC [1] does not provide guidance for temperature loading in a tunnel and the design team did not find any other references that addressed temperature ranges, gradients or loading in tunnels.

Another question raised at the design stage was the necessity of providing joints in the Tunnel. In general, joints are not desirable as they provide discontinuity in the structure, reduce the potential for load sharing, and increase the risk of corrosion. However, joints are sometimes necessary to release stresses from differential settlements, thermal movement, and shrinkage. Tunnel design references researched for this project did not provide clear guidance in this matter.

These questions were discussed with The City of Calgary (The City) and it was agreed that it would be beneficial for future projects to use the observations from this tunnel as design guidance; therefore, a series of temperature and displacement sensors were installed during construction and data has been collected from the sensors since the Tunnel opened in May 2014.

2 - TUNNEL STRUCTURE DESIGN AND CONSTRUCTION

The main structure of the Tunnel consists of a cast in-place reinforced-concrete rigid frame on spread footings with two clear spans of 17 m each and a total length of 620 m. Figure 1 shows a picture of the Tunnel after construction.

Structural design of the Tunnel was based on the CHBDC CAN/CSA S6-06 standard [1] and completed in accordance with The City of Calgary 2007 Design Guidelines for Bridges and Structures (Design Guidelines) [2]. The primary model for structural analysis was a two-dimensional (2D) linear finite element model using frame elements. More detailed 2D and three-dimensional (3D) models with frame or shell elements were used as required to check construction staging, and the effects of block outs, conduits, and openings in the walls. Analysis for lateral surcharge due to aircraft, braking force, and additional earth pressure due to earthquake was provided by the project geotechnical sub-consultant (Thurber Engineering Ltd.). Design of the structure was primarily governed by the requirement to limit crack widths at service loads below the limits provided in The City's Design Guidelines [2] which were 0.25 mm in portals and first two sections in from portals, and 0.3 mm in other locations.

A cut-and-cover construction method was used, with the top of the structure predominantly below the top elevation of the surrounding bedrock. Depending on the location along the length of the Tunnel, backfill was either a free-draining, graded granular material, or native material with a 1-m-wide, free-draining gravel 'chimney' layer next to the structure. Perforated drainage pipes were installed next to the footings, both inside and outside of the walls, to collect and carry groundwater into the storm system. The structure was designed based on a drained system, though it can resist 7 m of water as an extreme load case. Figure 2 shows a typical section of the Tunnel.

To facilitate construction, the structure was divided into fifty 12.5-m long casting segments along its length (lengths varied for the end segments). The segments were cast using an alternating or checkerboard steel formwork system. Odd-numbered segments (called lead segments) were cast first, and then even numbered segments (called infill segments) were cast in-between completed lead segments. Casting started from the middle of the Tunnel, progressing outwards in both directions.

Horizontal construction joints in segments were only between the walls and the footings at 150 millimetres (mm) above the top of the footing. The first 150 mm of the wall was required to be cast with the footings to facilitate wall form installation. An external water stop was installed covering both the construction joint and the wall-footing corner (in case of any cracking from applied moments). The walls and roof slab for each segment were poured monolithically, which helped prevent differential shrinkage between these elements.

To minimize the possibility of differential settlement in the backfill, Tunnel segments under the paved portions of the runway have a continuous full load carrying structural approach slab (extending to undisturbed bed rock) supported on drilled concrete piles. Sections under taxiways, shoulder portions of the runway, and service roads have a pinned, slab-on-grade approach slab supported on full height granular fill. Tunnel portals at both ends consist of cast-in-place reinforced-concrete retaining walls.

Longitudinal construction joints were located at 12.5 m intervals based on form length. The majority of these joints were considered control joints and were designed as a weaker section to absorb cracking but maintain continuity for load sharing. To serve that purpose, only half of the longitudinal reinforcement was continued between segments at these joints. Cast-in reglets at the joints were filled with sealants to help limit moisture ingress.

Instead of acting as control joints, some of the longitudinal construction joints were designed as movement joints. Located at multiples of three or four construction joints (37.5 or 50 m), these joints were placed in locations of cross-section change or in segments with a larger depth of fill where the load sharing for aircraft loading was not as significant. There was a complete separation of the structure across the movement joints, except for sleeved glass-fibre-reinforced polymer (GFRP) dowels (see Figures 3 and 4). These dowels allowed for longitudinal movements due to temperature fluctuations or shrinkage, as well as relief of accumulated forces or stresses from lateral or vertical ground movements (though significant ground movements were not expected from the bedrock foundation and surrounding soils). A bond breaker applied to the cross-sectional area to prevent bonding of the concrete between segments. The footings were poured monolithically between the movement joints and did not have longitudinal control joints.

3 – INSTRUMENTATION

3.1 – Overview

As introduced in Section 1, a remote wireless temperature and movement monitoring system was installed during construction of the Tunnel. There were two main goals of the system:

1. Measure and record surface and internal concrete temperatures along both the length of the structure and across segment widths
2. Measure and record horizontal, vertical and in-plane movements at two movement joint locations.

The monitoring system is composed of four main wireless elements:

- 37 temperature sensor assemblies spread out along the length and width of the Tunnel
- 4 displacement sensor assemblies (two one-dimensional [1D] or uniaxial sensors, and two 3D or tri-axial sensors) located at two movement joint locations
- 2 SeniMax™ data bridges (data recorders)
- 2 signal repeaters.

The wireless monitoring system was supplied by Resensys, installed by Metro Testing, and monitored by GOAL Engineering.

3.2 – Materials

SenSpot™ wireless sensors were used for both temperature and displacement monitoring. The sensors are sealed units containing a microcontroller, a directional antenna and a replaceable prime lithium-ion battery. The microcontroller provides an internal temperature reading that was calibrated to measure concrete surface temperatures. The sensors have a working temperature range of -40 to +65°C.

The temperature assemblies are connected with two thermaprobes which were embedded in the Tunnel concrete. The probes operate with a resolution of 0.5°C. When combined with the microcontroller, each assembly can measure three unique temperatures through the thickness of a structural member. Figure 5 shows the typical installation for a temperature sensor assembly.

Each movement sensor assembly uses attachments that measure displacement relative to the sensor's position. The 1D sensors are equipped with a sliding element that measures translations along the length of the element. The 3D sensors use a target and a receiver to measure displacements in all three Cartesian planes (x-y, x-z, y-z). Both types of sensor have a measurement resolution of 0.1 mm. Figure 6 shows a typical movement joint sensor installation for a 1D and a 3D assembly.

The SeniMax™ data bridges collect the data from the individual SenSpots™ and transmit data packages at regular intervals to a remote server through a mobile network. The data bridges operate primarily on solar power with a panel placed on top of the unit and a secondary battery for backup power.

3.3 – General Sensor Layout

The 37 temperature sensors were installed in a total of 12 segments in the structure, spanning the full length of the Tunnel. The number of sensors per segment ranged from 1 to 8, with 2 sensors being the most common arrangement. The layout of the temperature sensors was chosen to provide temperature profiles both along the Tunnel length and across the width of individual segments.

The four movement sensors were placed at two joint locations where displacements were expected. One pair was placed underneath the edge of the runway slab, and the other pair underneath the edge of a taxiway slab. Each pair was made up of one 1D sensor and one 3D sensor. Three of the four sensors were mounted on the Tunnel walls, while the fourth was mounted to the soffit of the roof slab.

The two SeniMax™ data bridges were located at the portal entrances to the Tunnel. Each data bridge collects data from sensors in one cell of the Tunnel. For example, the SeniMax™ at the West Portal collects data from all of the sensors in the westbound cell. A signal repeater was installed in each cell to help transmit the signals from the individual SenSpots™ at the far end of a cell to the SeniMax™.

3.4 – Operation

The individual SenSpot™ sensors measure temperatures, movement or both every 6 minutes. Temperatures on the embedded thermaprobes are measured in degrees Celsius, while temperatures from the microcontroller are measured in degrees Fahrenheit and later converted to Celsius. Movements for the 1D and 3D sensors are measured in millimeters. Data is sent from the individual sensors to the SeniMax™ data bridges, boosted along the way by the signal repeaters. The data are stored by the SeniMax™ data bridges and wirelessly transmitted to the remote server every hour. Data can be viewed in real-time with a software program tied to the sensors. More information on the system installation, layout and operation are described in Murdoch et al. [3].

4 – OBSERVATIONS – TEMPERATURES

4.1 – Data Analysis

This section provides a summary of the preliminary observations from the temperatures recorded in the Tunnel from April 11, 2014, to December 22, 2016. Section 4.2 focusses on the extreme temperatures, and Section 4.3 discusses the observations on temperature differentials through the thickness of the walls or slab. It should be noted that temperature recording continued until May 2017, and data analysis is still in progress at the time of writing.

During data analysis, efforts were made to filter out erroneous readings as much as possible and to use the numbers that seemed reasonable when compared to the adjacent measurements. Considering that most of the results are presented in terms of averages throughout the Tunnel, the presence of anomalous data in a few locations will not affect the results significantly. The primary objective of this monitoring program was to get a general sense of temperature trends in the Tunnel, and accuracy of the results in the range of 1°C or 2°C is not a concern.

4.2 – Temperature Range

The raw data was collected in 1-hour intervals for each probe. Temperature range analysis is based on the maximum and minimum temperatures recorded for each day. Complete graphs for recorded temperatures and corresponding comparisons are presented in a report submitted to The City [4] and some samples are presented here.

For the slab and exterior walls, the term “surface” refers to the temperature of the concrete surface in contact with the air (Figure 5), “dirt surface” is the temperature recorded by the probe embedded in concrete close to the earth fill. For the interior wall, the term “surface” refers to the temperature of the concrete surface in contact with air in the north cell, and “cover” is the temperature recorded by the probe embedded in the concrete within the cover (100 mm) close to the south cell. For all elements, “mid-depth” is the temperature located at the mid-depth of the element (0.5 m for walls and 0.625 m for the top slab).

It was recognized that the end sections of the Tunnel are more exposed to the external environment and may experience wider temperature fluctuations. The temperatures, therefore, were averaged along different longitudinal sections of the Tunnel to capture this effect over the Tunnel length. The following list shows the construction segment numbers in each section:

- 0-100 m: Segments 1, 3 and 7 (western end)
- 100-520 m: Segments 11, 15, 19, 28, 35 and 41
- 520-620 m: Segments, 45, 48 and 50 (eastern end).

Figures 7 and 8 are samples of recorded temperatures. These graphs show the average of maximum and minimum daily temperatures recorded along the length of the tunnel for the slab at different levels for a period of 1 year. The maximum and minimum daily temperatures recorded at the Environment Canada Airport Weather (YYC) Station are also shown for reference. The following list of observations resulted from comparing the daily maximum and minimum temperatures, recorded at different depths and averaged over the longitudinal sections, listed for the walls and the slab:

- **Slab:**
    - Maximum and minimum temperatures in the slab surface follow the YYC temperature fluctuations but with a smaller magnitude. Average temperatures of different longitudinal sections are within few degrees Celsius. End sections show higher peaks, with peaks more pronounced in the summer months. This difference is not considered significant.
    - In general, temperatures at mid-depth of the slab do not fluctuate as much as those recorded at the surface. Section 0-100 shows some fluctuations, with a time lag from YYC temperatures. The temperature difference between the end and internal sections is greater for mid-depth temperatures compared to surface temperatures, and greater during very hot and very cold periods.
    - Temperatures at slab mid-depth in the internal portion of the Tunnel resemble a sinusoidal function with very small or no fluctuations. These temperatures are generally lower in the summer and higher in the winter compared to the end sections and seldom go above 20°C or below -5°C.
    - The temperature difference between the three longitudinal sections is greater at dirt surface and could be up to about 20°C. Like temperatures at mid-depth, the temperature range at the dirt surface for the internal portions of the Tunnel is smaller compared to the end segments (cooler in summer and warmer in winter) and much smaller compared to YYC temperatures.
- **Exterior walls:**
    - The surface temperatures recorded for the exterior walls had much larger fluctuations compared to the slab surface temperatures, especially at the end sections. The maximum recorded temperatures during the summer months for the eastern end (520 - 620 m) are within few degrees Celsius of the YYC temperatures. During winter, however, the minimum temperatures do not get as low as the YYC minimum temperatures

- In general, the temperatures recorded for the exterior walls at the mid-depth and dirt surface levels have very small fluctuations, and temperatures of different longitudinal sections are very similar. The temperature range for the mid-depth and dirt surface probes is 20°C < *t* < -5°C, where *t* is the recorded temperature.

- **Centre wall:**
  - Surface temperatures recorded for the centre wall have a pattern similar to the surface temperatures recorded for the external walls.
  - The temperature fluctuations observed at the mid-depth of the centre wall are smaller than the fluctuations of surface temperatures for the centre wall but larger than the fluctuations at mid-depth of external walls. This makes sense, as the centre wall is exposed to ambient air temperatures on both sides.
  - Temperatures recorded at the cover level (100 mm below the concrete surface) were found to be very similar to mid-depth temperatures in the centre wall. This suggests that the high temperature fluctuations occur mainly in a thin surface layer (less than 100 mm thick).

Graphs in Figures 9 and 10 compare the minimum recorded temperatures for the slab and exterior walls at the surface and dirt levels, respectively. The temperatures were averaged along the entire length of the Tunnel (0-620 m). In general, the difference between the wall and slab temperatures was slightly more during winter. Temperatures recorded at the mid-depth were very close to the dirt level temperatures for both the walls and the slab and are not shown for the sake of simplicity.

It should be noted that, in general, the dirt surface probes in the wall elements are adjacent to a higher depth of fill than dirt level probes in the slab sections. The height of fill above the slab varies from 0.6 m at the end sections to about 4 m in the internal portions of the Tunnel. A wall section at a sensor location will typically have an additional 3 m of fill. Even at the ends of the Tunnel, the portal retaining walls will protect the dirt surface of the wall from ambient thermal effects. This may be one of the reasons that the temperatures at dirt surface and mid-depths of the wall are similar for both the internal and end sections of the Tunnel.

From a design point of view, the temperature range for the slab is more crucial than the temperature range for the walls, as temperature variations in the slab develop bending moments in the frame structure. In addition, the cold temperatures are more crucial because they develop bending moments in the structure that are in the same direction as the bending moments applied from soil pressure. Observations from wall to slab comparisons include:

- Surface temperatures for the walls and the slab are generally similar. Recorded temperatures follow the YYC temperature trend but with a smaller magnitude of daily fluctuations. Wall temperatures were found to have larger peaks (or spikes) and the temperature difference between elements became larger with minimum temperatures in cold periods. Surface wall temperatures were found to be warmer in summer and colder in winter than slab temperatures.
- Daily temperature fluctuations do not penetrate to the mid-depth or dirt surface of both the walls and the slab. Instead, these temperatures followed a mild seasonal trend with the range of -5°C to +20°C with the wall mid- depth and dirt level temperatures being colder during the summer and warmer during the winter (likely due to larger depth of the fill at the walls).

For design, a temperature range based on an average temperature through the thickness of the section and a temperature gradient are required. The temperature range of the entire structure (slab and walls) is needed to estimate the movement in the longitudinal joints. The temperature range of the slab plus the temperature gradient for both the slab and walls is applied to the structural model to design the frame structure.

Figures 11 and 12 present the variations of the average maximum and minimum daily temperatures for external walls and the slab. Average temperatures were obtained conservatively by averaging the maximum and minimum daily recorded temperatures at the three probes locations for each sensor. Observations from these two graphs include:

- Average temperatures follow a mild seasonal trend between -5°C and + 20°C, with minor daily fluctuations.
- Average wall and slab temperatures are very similar, with the difference being less than 3°C.
- The slab is slightly colder than the walls in the winter and warmer in the summer.

Table 1 presents the average maximum and minimum daily temperatures recorded in the Tunnel and compares them with two reference points: the design values for Calgary given in current edition of the *Canadian Highway Bridge Design Code, Standard S6-14* (CAN/CSA S6-14) [5] and the official temperatures recorded at the YYC Station by Environment Canada.

The first row of the table presents the maximum and minimum mean daily temperatures obtained from CAN/CSA S6-14 [5] Figures A3.1.1 and A3.1.2 for Calgary. The second row gives the effective temperatures for concrete structures based on CAN/CSA S6-14 [5] Table 3.8. Rows 3 and 4 show the design temperature range modified from effective temperatures in accordance with the depth of the superstructure (CAN/CSA S6-14 [5] Figure 3.5). Rows 5 and 6 note the temperatures obtained from Environment Canada measurements at the YYC Station. Row 5 shows the highest and lowest temperatures recorded during the time interval under consideration (April 2014 to December 2016), and row 6 shows the highest and lowest mean daily temperatures during this period. Comparing YYC (row 6) with CAN/CSA S6-14 [5] (row 1), there is good agreement between the maximum mean daily values, with a difference of 4°C, but much less of an agreement between the minimum mean daily values, with a difference of 15°C.

Rows 7, 8 and 9 show the average of maximum and minimum daily temperatures recorded in the Tunnel. The values were first averaged through the structure's thickness (surface, mid-depth and dirt/cover) and then averaged for all sensors in the slab, external walls and internal wall, respectively.

Table 1. Extreme Temperature Comparisons

Source	Description	Tmax [°C]	Tmin [°C]
CAN/CSA S6-14 [5]	Mean daily temperature - Calgary	28	-38
	Effective temperature - Concrete	38	-43
	Design temperature - Walls, 1 m	36	-39
	Design temperature - Slab, 1.25 m	35	-38
YYC Station	Daily high and low temperature	34	-27
	Mean daily temperatures	24	-23
Recorded Daily	Slab average temperature	22	-7
	External walls average temperature	21	-7
	Internal wall average temperature	25	-11

The maximum and minimum daily temperatures are similar for the slab and external walls, with an absolute temperature range of about 29°C. The temperature range for the internal wall is slightly higher at 36°C, which is expected, considering that the internal wall is exposed to air on both sides; whereas, the external walls and slab are exposed to air on one side and dirt on the other side.

Based on the recorded values, the slab was exposed to a temperature range of 29°C, compared to a CAN/CSA S6-14 [5] slab design temperature range of 73°C. The possibility of the Tunnel experiencing more severe winters can be accounted for by two comparisons. Comparing the mean daily temperature ranges from the CAN/CSA S6-14 [5] and the YYC Station (row 1 with row 6), there is an absolute difference of 19°C. Comparing the YYC Station daily high and low temperature range and the recorded slab temperature range (row 5 with row 7), there is a relative ratio between the ranges of 2:1 (61°C versus 29°C). If the absolute difference of 19°C is applied to the recorded slab temperature range at the ratio of 2:1, the slab range can be increased by a value of approximately 10°C. This will increase the overall potential Tunnel temperature range to about 39°C, which is still 34°C less than the temperature range provided by CAN/CSA S6-14 [5].

Assuming a construction temperature of 15°C, the design temperature drop for the slab is 53°C, per CAN/CSA S6-14 [5]. Using the same approach, a theoretical slab minimum temperature of -17°C can be assumed. This would result in an actual temperature drop of about 32°C.

As noted, the numbers given in Table 1 are averaged for all sensors along the entire length of the Tunnel for each frame member (wall or slab). It is recognized, however, that the end sections of the Tunnel are more exposed to the external environment; therefore, they may experience wider temperature fluctuations. Table 2 provides average maximum and minimum daily values for the slab, averaged along different longitudinal lengths of the Tunnel. As expected, temperature ranges are higher at the end sections and lower in the internal section. However, the difference is not considered significant.

Table 2. Longitudinal Temperature Comparison

Recorded Average Daily Slab Temperature	**Tmax [°C]**	**Tmin [°C]**
Entire Tunnel	22	-7
0-100 m	23	-14
100-520 m	21	-6
520-620 m	25	-8

4.3 – Temperature Differentials

One of the objectives of this project was to determine an estimate of temperature gradients to be used for tunnel design by measuring the temperature differentials through the thickness of the members. Complete graphs for temperature differentials are presented in the report to The City [4]. Figures 13 and 14 were selected as samples that show the temperature differentials in the slab between the dirt and surface levels and the dirt and mid-depth levels, respectively. Each graph presents the maximum (absolute value) positive and negative temperature differentials. For each location, these values were obtained by subtracting the recorded temperatures at different depths, selecting the ones with the largest absolute values (positive or negative) and averaging them along the different longitudinal sections of the Tunnel. Positive means that the level closest to the surface is warmer. Temperature differential observations for the slab, external walls and centre wall are as follows:

- In general, the temperature differentials were significant between the surface and mid-depth.
- Temperature differentials between the dirt surface and mid-depth for the slab and external walls were usually less than 2-3°C, with the maximum being less than 5°C. Similar behaviour was noted for the centre wall between the cover and mid-depth levels. For the centre walls, the cover probe is at a depth of about 100 mm from the surface of the south cell. Assuming that the south and north cells have similar ambient air temperatures, it can be hypothesized that the temperature differentials occur mainly in a thin (100-mm) surface layer.
- The seasonal trend (sinusoidal shape) that was observed in the maximum and minimum temperatures is not seen with the temperature differentials. The differentials were affected mainly by the daily fluctuations and, to a lesser degree, by the seasonal temperature trend at dirt surface (followed closely at mid-depth).
- In general, the end sections have larger temperature differentials, however, there are some periods when the differentials for the internal section of the Tunnel were larger.
- Peak positive gradients were seen both in summer and winter with similar magnitudes. Peak negative differentials only occured in winter.
- Both the walls and the slab have daily temperature differentials in the range of ±10°C throughout the year, with peaks up to ±18°C.

Table 3 presents a comparison between the temperature differentials measured in the Tunnel with the values provided in CAN/CSA S6-14 [5], Clause 3.9.4.4 and Figure 3.6 for the design of concrete bridges. For the slab and external walls, this was considered the temperature at the surface exposed to traffic (air) minus the temperature at the surface exposed to backfill (dirt). Data are presented for both positive and negative temperature differentials. The values are similar for the walls and the slab, and both are much higher than the recommended code values. Table 4 presents a longitudinal comparison of the temperature differentials averaged over the end and internal segments.

Table 3. Temperature Differential Comparison

Description	**∆Tpositive [°C]**	**∆Tnegative [°C]**
CAN/CSA S6-14 [5] (Figure 3.6)	+10	-5
Recorded slab average	16	-18
Recorded external wall average	14	-18

Table 4. Longitudinal Temperature Differential Comparison

Recorded Average Daily Slab Temperature Differential	**∆Tpositive [°C]**	**∆Tnegative [°C]**
Entire Tunnel	+16	-18
0-100 m	20	-17
100-520 m	16	-19
520-620 m	14	-15

It was observed that the temperature distribution through the depth of a given concrete section is not linear, and in general, the temperature differential between the air surface and mid-depth is higher than the temperature differential between mid-depth and the dirt surface. Figure 15 shows temperature distributions along the depth of the slab for a positive temperature differential, and Figure 16 shows samples of temperature distribution along the depth of the slab for cases with high temperature differentials in sensors located in one section.

It should be noted that the temperature differentials stated in the code are for a linear temperature variation through the entire depth of the member. This is not the case for the temperature differentials observed in the Tunnel that occur in a smaller layer, as observed for the centre wall. For future designs, an equivalent linear temperature gradient could be calculated. One approach could be to calculate a temperature differential that, with a linear distribution through the full depth of an element, will produce the same moment about the mid-section as the temperature differentials observed in the Tunnel. This equivalent temperature gradient needs to be calculated on a pure moment basis, so the temperature differential distribution needs to be adjusted to remove the axial force component, considering that the axial force component is part of the temperature range loading.

Figure 17 shows an example of this calculation for the -18 °C temperature differential, as measured on Figure 16. In this case, the equivalent temperature differential for the full depth is -9.5°C. Based on this approach, the measured temperature gradients are covered if a ±10 °C temperature differential is used through the full section thickness for both summer and winter temperatures.

5– OBSERVATIONS – MOVEMENTS

5.1 – Data Analysis

This section provides a summary of the preliminary observations from the movement sensors in the Tunnel from May 1, 2014, to December 22, 2016. As mentioned in Section 3, four movement sensors were installed in the Tunnel. Two of them are located in the movement joint between segments 12 and 13 (12-13) and two of them between segments 32 and 33 (32-33) (Figure 3). At each location, one of the sensors was designed to measure triaxial movements and one to measure uniaxial movements. The uniaxial sensors only recorded the longitudinal movements (x-axis, horizontal and parallel to the roadway), and the triaxial sensors measure movements in two more directions: transverse (y-axis, horizontal and perpendicular to road way) and vertical (z-axis). The numbers recorded represent the relative displacement between the two Tunnel segments at movement joint locations. As noted in Section 3, all four sensors also have an microcontroller that measures the internal temperature of the sensor. Data collection was completed in May 2017, and data analysis is still in progress.

The 12-13 sensors are located at mid-height of the north and south walls, with the north wall sensor being triaxial. During the monitoring period, it was observed that the triaxial sensor was recording erroneous results. This sensor was removed and replaced with a uniaxial sensor measuring longitudinal movements only.

For the 32-33 location, the triaxial sensor is located high in the north wall close to the slab, and the uniaxial sensor is located in the middle of the slab in the north cell. The uniaxial sensor was malfunctioning for a period between 2015 and 2016 and has since been repaired.

Movement data were collected hourly, and the graphs are plotted from all recorded numbers (without any averaging of maximum or minimum values). Temperature data presented in each graph are the recorded internal temperature values.

5.2 – Movement Observations

Figure 18 provides a sample of the recorded longitudinal movements, and the following summary lists observations from recorded movements:

- In general, the longitudinal movements follow the temperature changes.
- Movement variations have mainly a seasonal trend, with small, short-term fluctuations.
- The observed movement range is about 10 mm. It seems that the graphs are cut off at the peaks, which could be due to sensor limitations.
- In general, the transverse and vertical movements also follow the seasonal trend of temperature changes, but with a smaller magnitude comparted to longitudinal movements.
- The magnitude of fluctuations for transverse and vertical movements are larger when compared to the longitudinal measurements of the uniaxial sensors.

The Tunnel sections on either side of Joint 12-13 have a length of 50 m, whereas the sections on either side of Joint 32-33 are 37.5 m long. As noted in Section 4, the average temperature range observed for the Tunnel was 25°C (between -5°C and +20°C). Assuming free longitudinal movement, the expected thermal movement would be approximately 13 mm for Joint 12-13 and 10 mm for Joint 32-33. The measured movements were 8 mm and 10 mm, respectively. The fact that the sensors at Joint 32-33 have a larger movement might be due to the location of the sensors. The sensors at Joint 12-13 are installed in the wall, which could be more restricted by the foundations that are dowelled into the underlying bedrock at this location. The measured movements are well within expected values.

Joint 12-13 is located very close to one of the taxiways, and Joint 32-33 is almost at the edge of the runway. The depth of fill above the slab at these location is about 2-3 m. The movement sensors were located at these joints to see whether taxiway and runway loading would affect the structure. The new runway was opened in June 2014. To date, no fluctuations of any significance have been observed to suggest loading affects from air traffic.

6 – SUMMARY AND CONCLUSIONS

The Calgary Airport Trail Tunnel is a 620-m-long roadway tunnel constructed under the Calgary International Airport's new parallel runway and three associated taxiways. The main structure consists of a two-span, cast-in-place, reinforced-concrete, rigid frame on spread footings. The Tunnel was designed to comply with CAN/CSA S6-06 [1]. The question arose during the design stage whether the Tunnel, which is a buried structure, would be subjected to the same temperature effects (range and gradient) as those provided in CAN/CSA S6-06 [1] for bridges.

Temperature and movement sensors were installed in the Tunnel to investigate temperature effects and tunnel movements. Temperature observations were compared to the values recommended by CAN/CSA S6-14 [5]. The discussion provided in this paper is a summary of preliminary observations based on simple averaging techniques. Any future design recommendations will require observations from similar projects and more rigorous statistical analysis.

Preliminary observations are summarized as follows:

- Observed temperatures and temperature range:
    - The average temperature range observed in the Tunnel is smaller than the range recommended in CAN/CSA S6-14 [5] for the design of bridges. The observed average temperature range is less than half of the design temperature range, with the difference increasing at colder temperatures.

- In general, average temperatures in the Tunnel have a seasonal trend (resembling a sinusoidal function) with very small or no daily fluctuations. These temperatures are generally lower in the summer and higher in the winter when compared to the outside temperatures and seldom go above +20°C or below -5°C.
- End segments of the Tunnel (first 100 m in from the ends) experience higher temperature ranges, but the difference is not considered significant.
- Daily temperature fluctuations affect the surface temperatures for both the walls and the slab but do not penetrate to mid-depth and dirt surface levels.
- Average temperatures for the walls and the slab are similar, with a difference of less than 3°C. The slab is slightly colder in the winter and warmer in the summer.

- Temperature differentials:
  - The average positive and negative temperature differentials (temperature difference between the surfaces exposed to the air and the surface against fill material) are both larger than the values recommended in the code.
  - Temperature distribution through the thickness is not linear. Temperatures at the Tunnel member mid-depth and the backfilled surface are very similar and do not show the larger fluctuations recorded for temperatures at the traffic (air) surface.
  - The seasonal trend (sinusoidal shape) that was observed in the maximum and minimum temperatures is not seen with the temperature differentials. The differentials are affected mainly by the daily fluctuations, and to a lesser degree, by the seasonal temperature trend at the dirt surface.
  - Peak positive gradients were observed both in summer and winter with similar magnitudes. Peak negative differentials were observed only in winter.
  - Both the walls and the slab have daily temperature differentials in the range of ±10°C throughout the year, with peaks as high as ±18°C.

- Movements:
  - In general, the longitudinal movements follow the temperature changes.
  - Movement variations have mainly a seasonal trend, with small, short-term fluctuations.
  - The magnitude of observed longitudinal movements range (8-10 mm) supports the observed average temperature range of -5°C to +20°C.

7 – REFERENCES

1. CSA Group. 2006. *Canadian Highway Bridge Design Code, Standard S6-06* (CAN/CSA S6-06). Mississauga: CSA Group.

2. The City of Calgary Transportation Infrastructure. 2015. *City of Calgary Design Guidelines for Bridges and Structures,* 5th ed. Calgary: The City of Calgary Transportation.

3. Murdoch, N., Azarnejad, A., Sharma, V. and Kroman, J., 2017. "Calgary Airport Trail Tunnel Temperature Monitoring". In *39th International Association for Bridge and Structural Engineering Symposium – Engineering the Future.* Vancouver BC: International Association for Bridge and Structural Engineering.

4. CH2M HILL Canada Limited (CH2M). 2017. *Airport Trail Tunnel Monitoring Report*. Prepared for The City of Calgary.

5. CSA Group. 2014. *Canadian Highway Bridge Design Code, Standard S6-14* (CAN/CSA S6-14). Mississauga: CSA Group.

8 – FIGURES

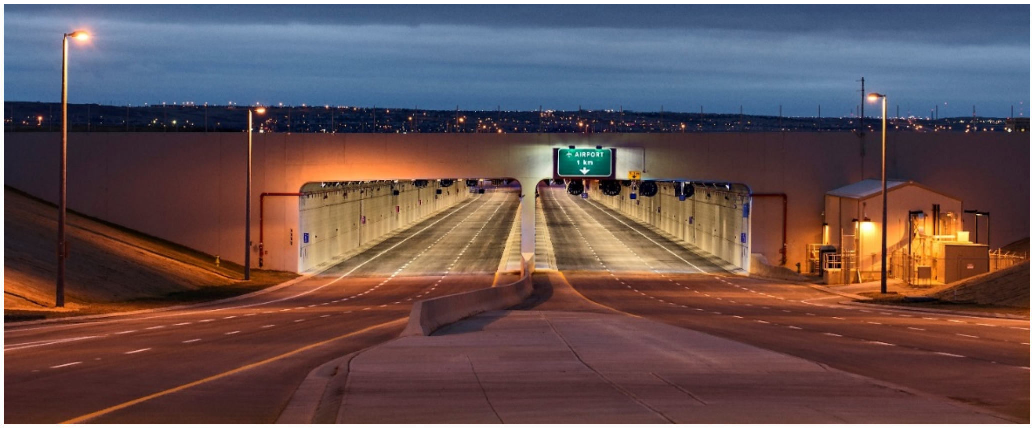

Figure 1. Calgary Airport Trail Tunnel (photo credit, Brad Heninger)

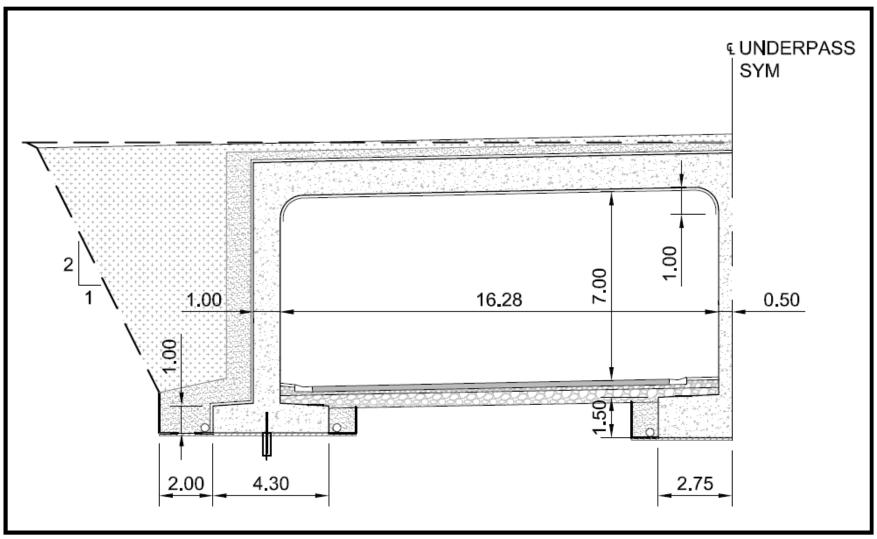

Figure 2. Typical Tunnel Section

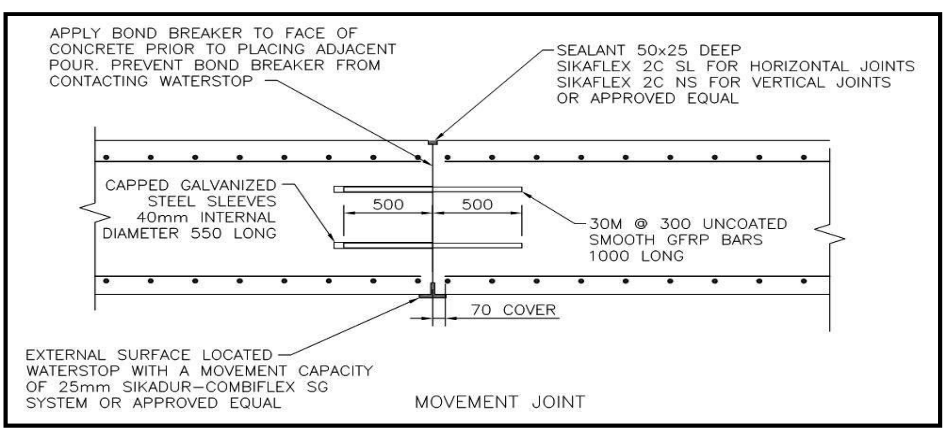

Figure 3. Movement Joint Details

Figure 4. Constructed Movement Joint

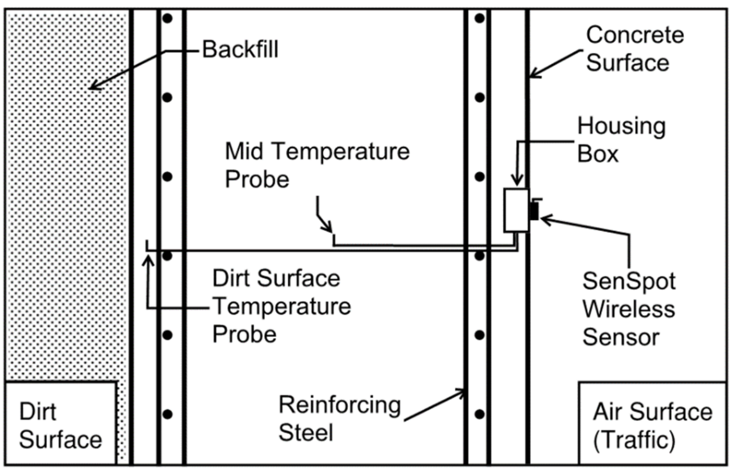

Figure 5. Typical Cross-section through Tunnel Wall Showing SenSpot^{TM} Sensor and Probes

Figure 6. Installation of the 1D and 3D Displacement Sensors

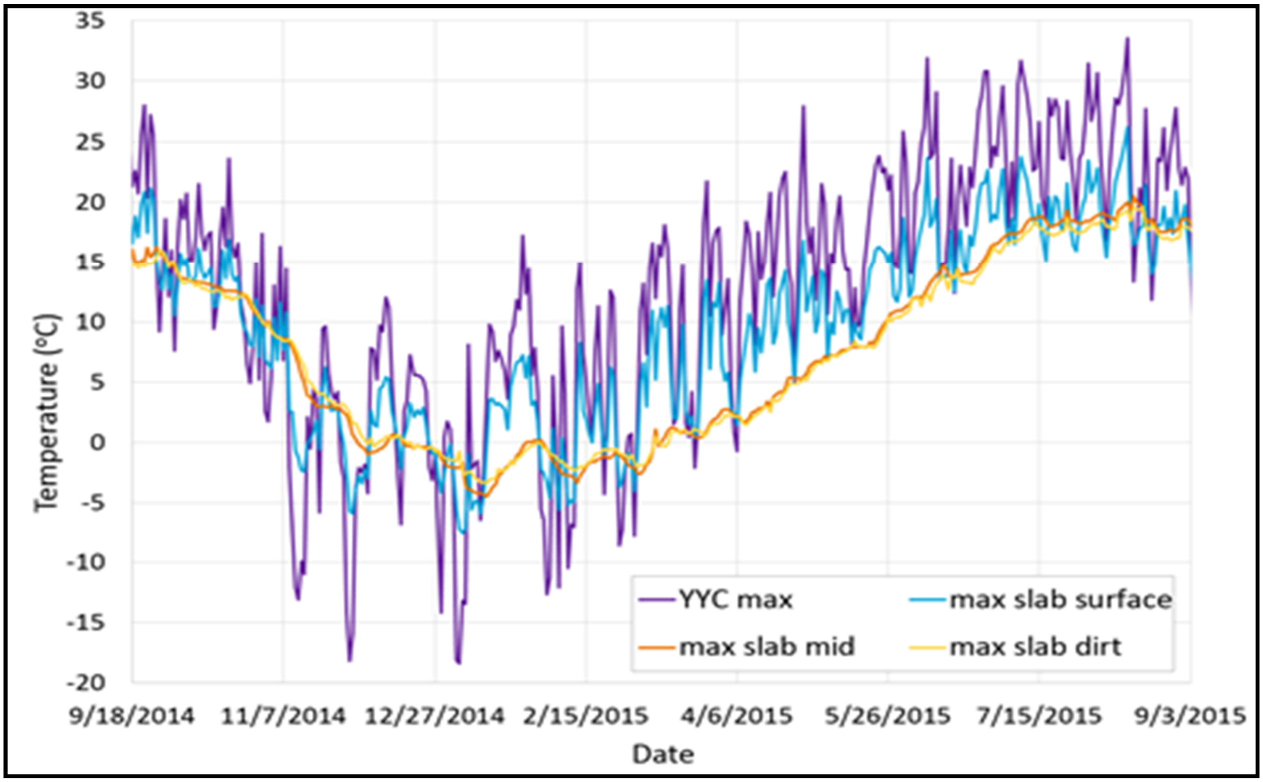

Figure 7. Average of Maximum Temperatures at Different Locations through the Depth of the Slab

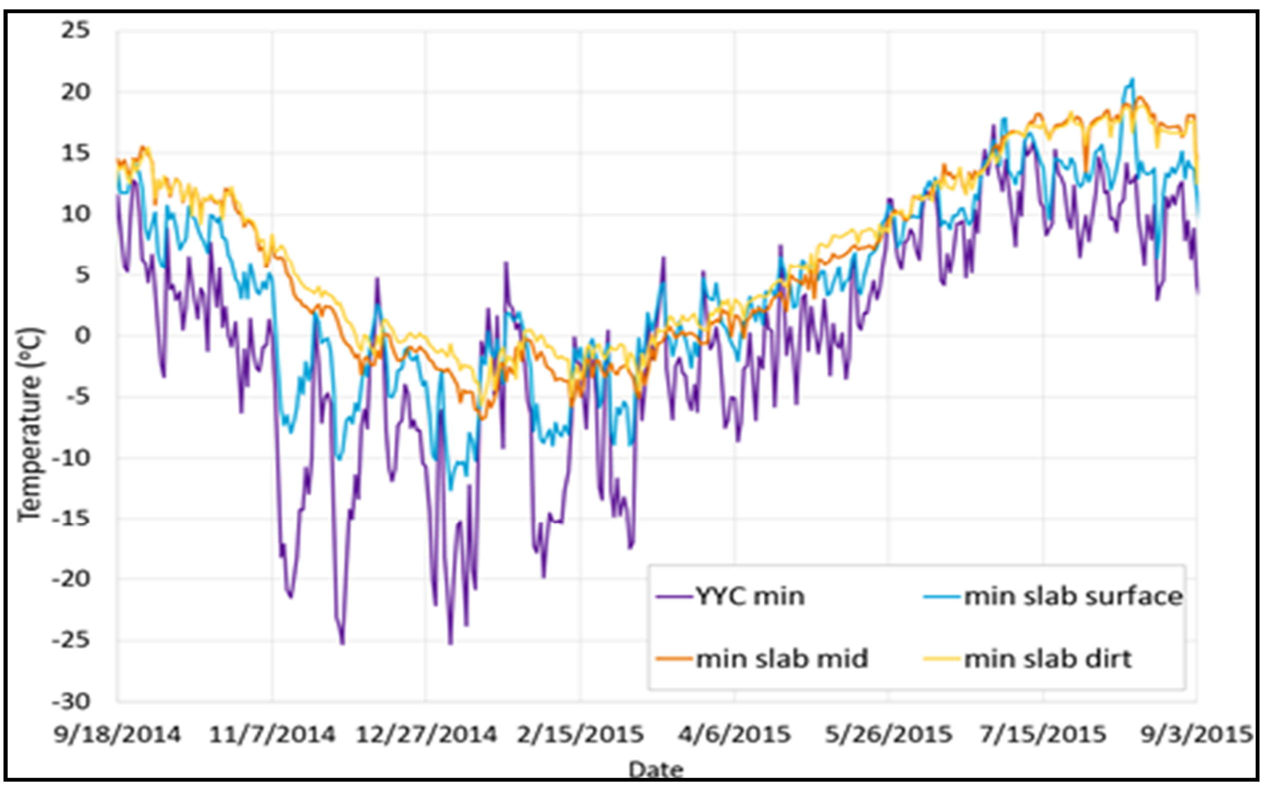

Figure 8. Average of Minimum Temperatures at Different Locations through the Depth of the Slab

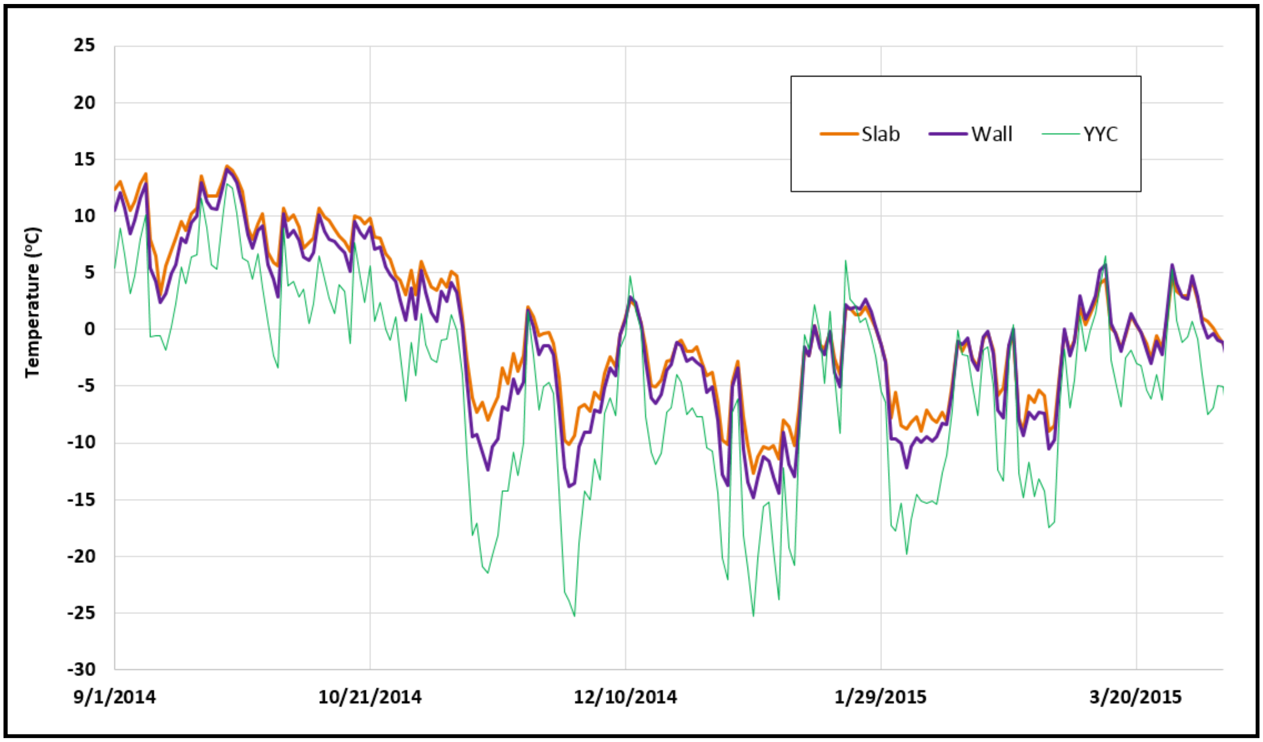

Figure 9. Average of Minimum Temperatures at Slab and External Wall Surfaces

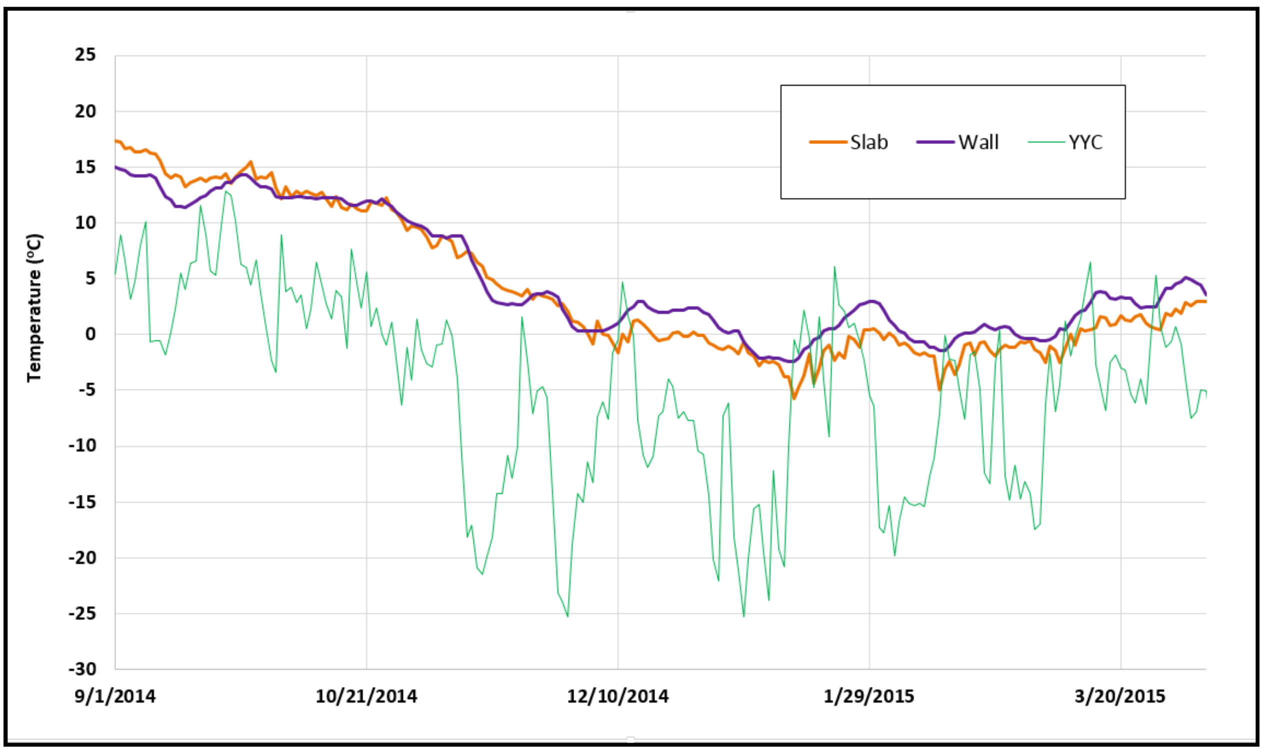

Figure 10. Average of Minimum Temperatures at Slab and External Wall, Dirt Side

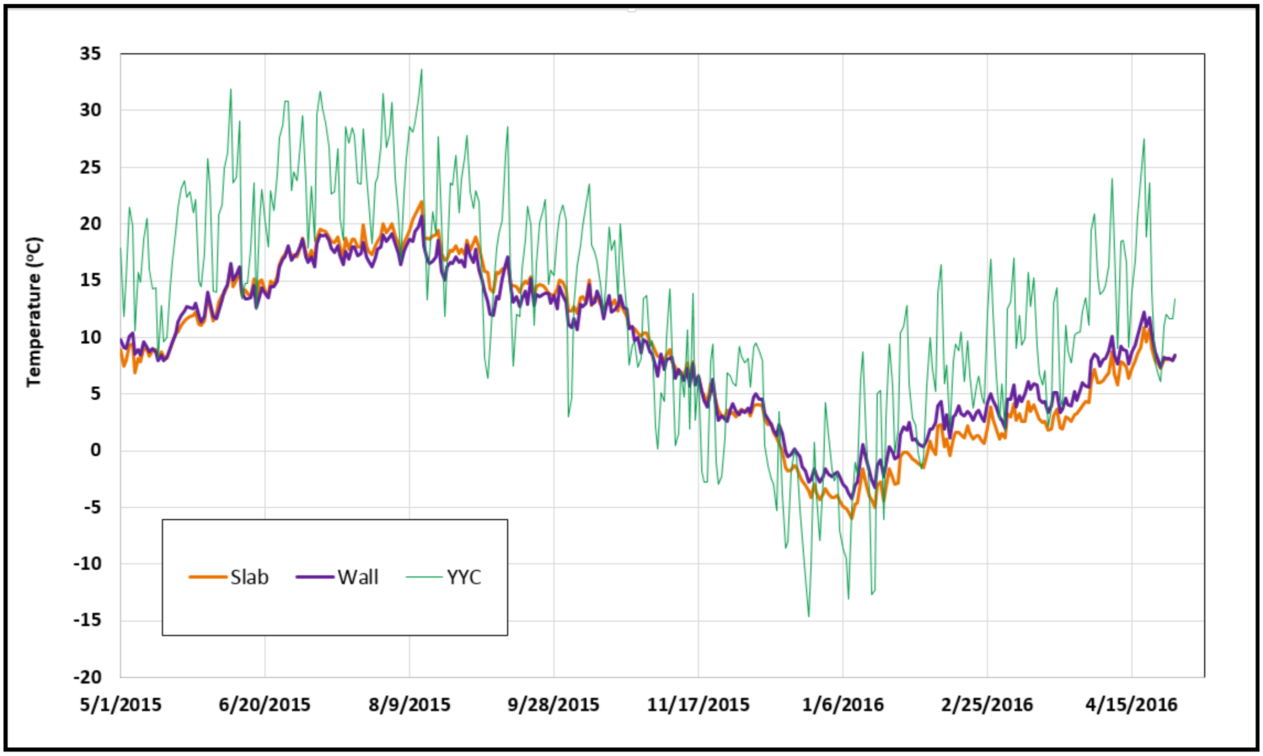

Figure 11. Average of Maximum Temperatures for all Wall or Slab Sensors

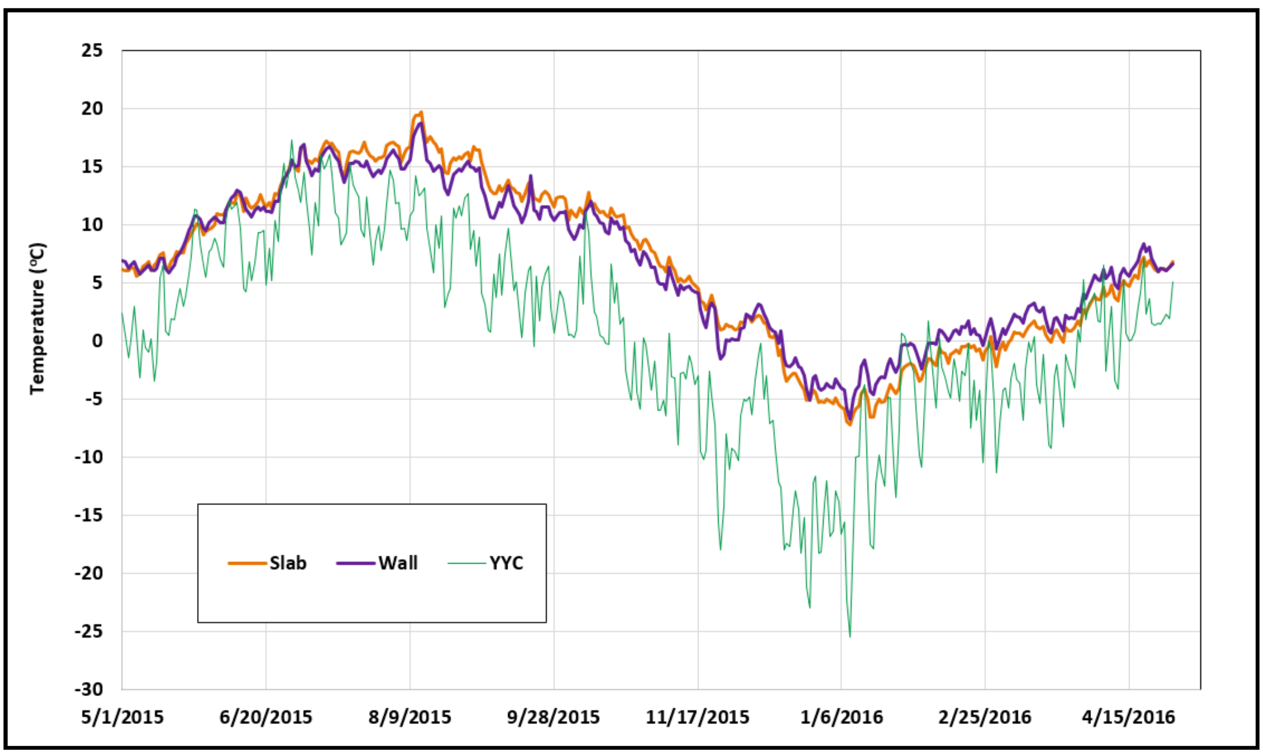

Figure 12. Average of Minimum Temperatures for all Wall or Slab Sensors

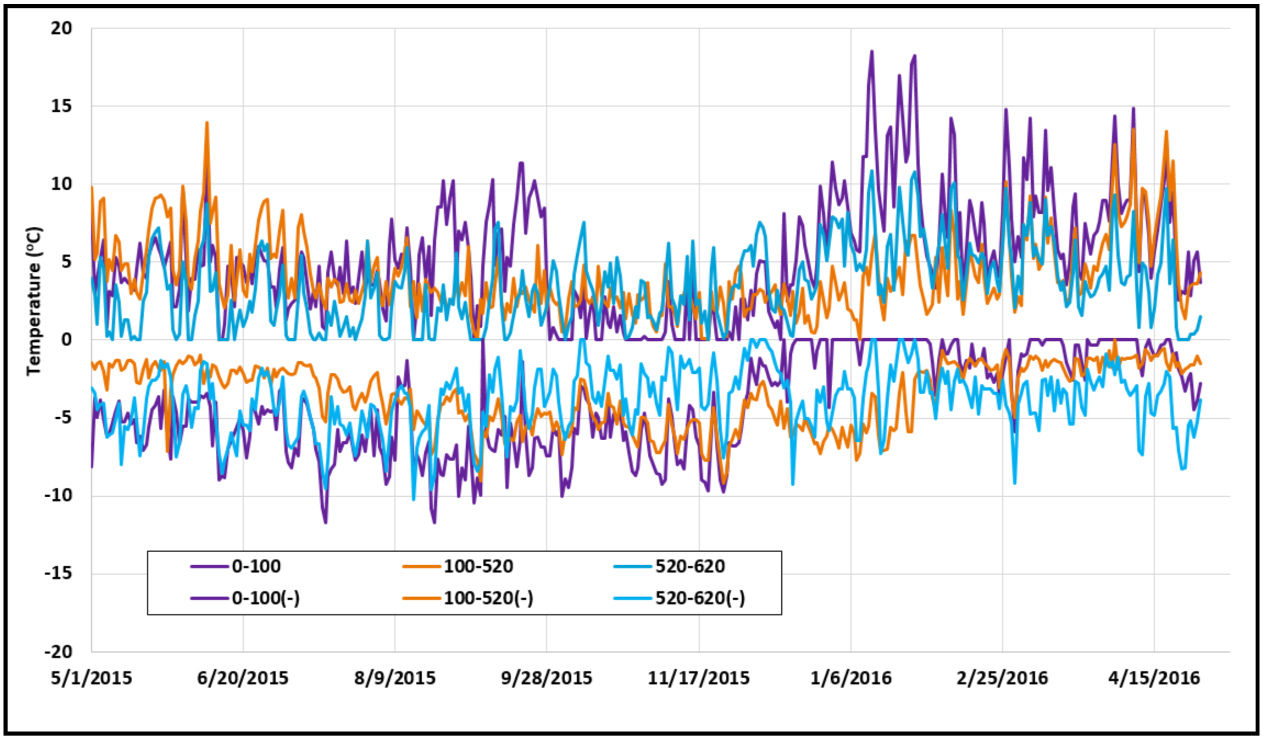

Figure 13. Average of Temperature Differentials between Surface and Dirt Levels for the Slab

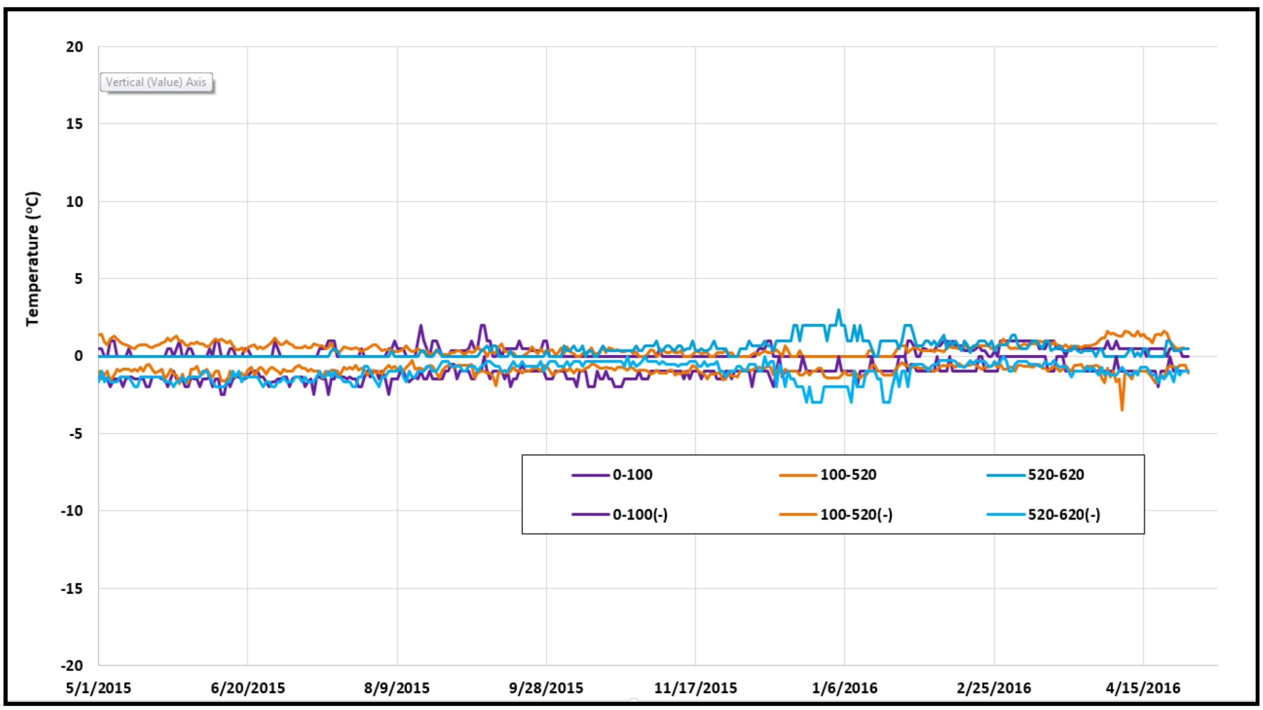

Figure 14. Average of Temperature Differentials between Mid-depth and Dirt Level for the Slab

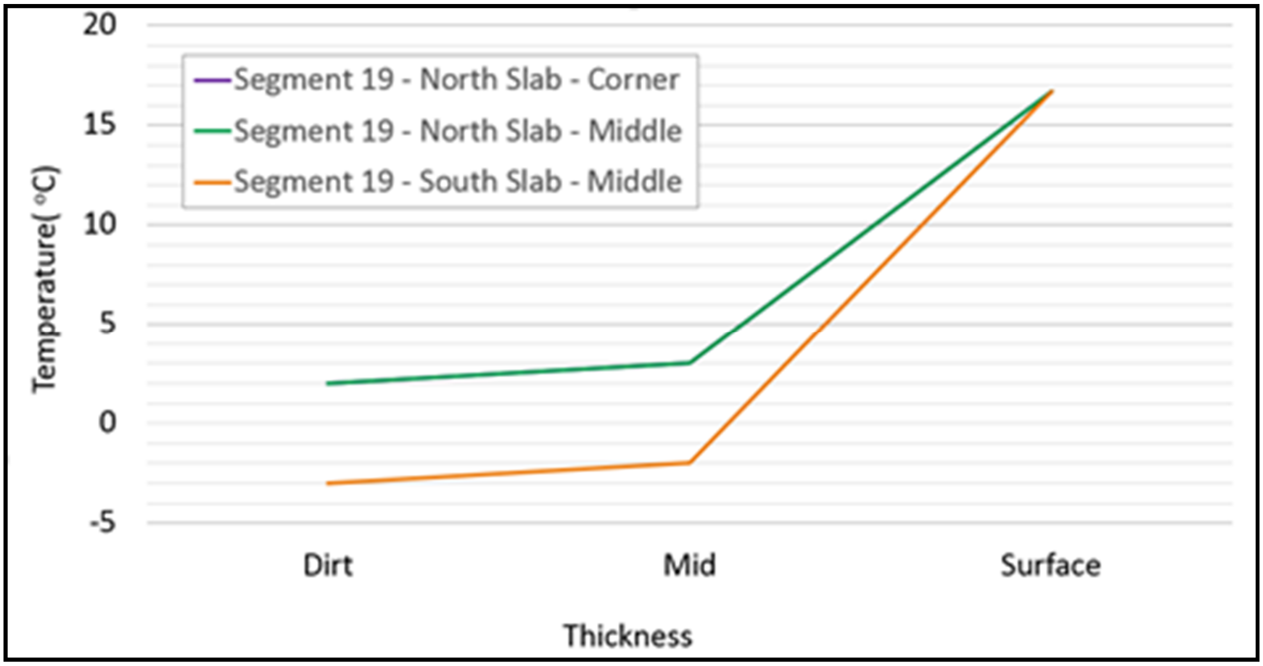

Figure 15. Temperature Distribution along Depth of Section for a Positive Temperature Differential

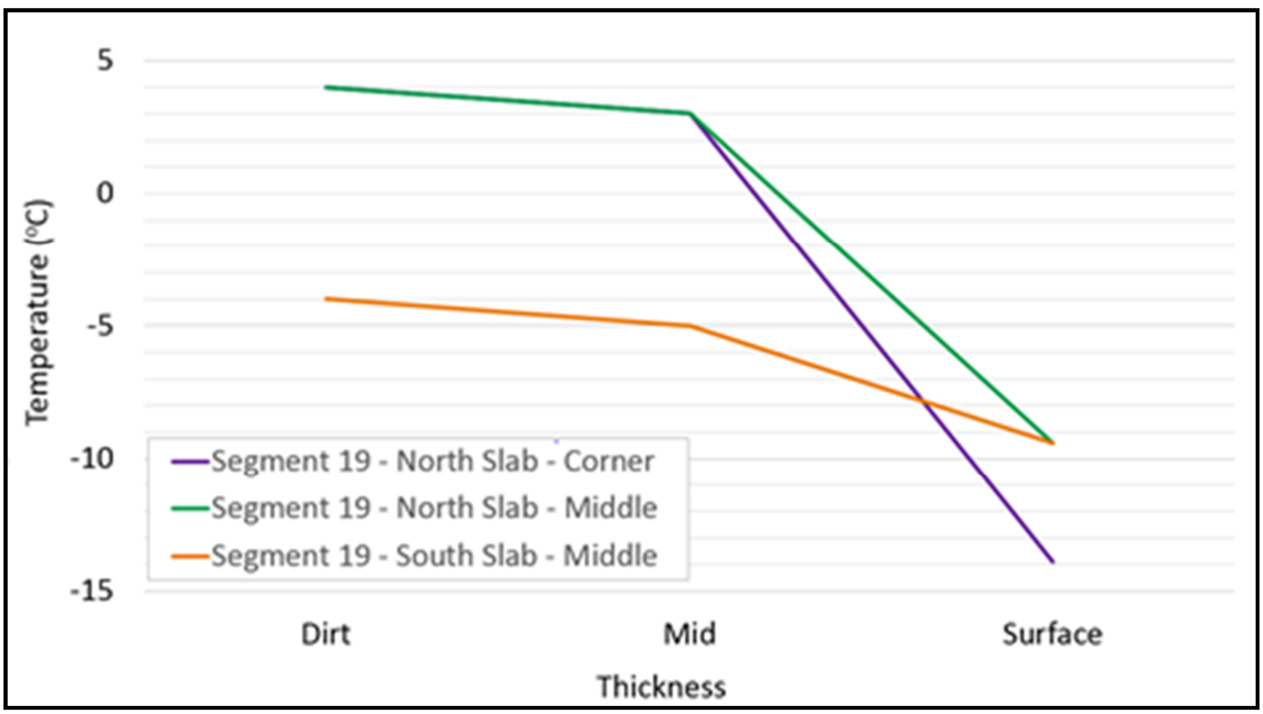

Figure 16. Temperature Distribution along Depth of Section for a Negative Temperature Differential

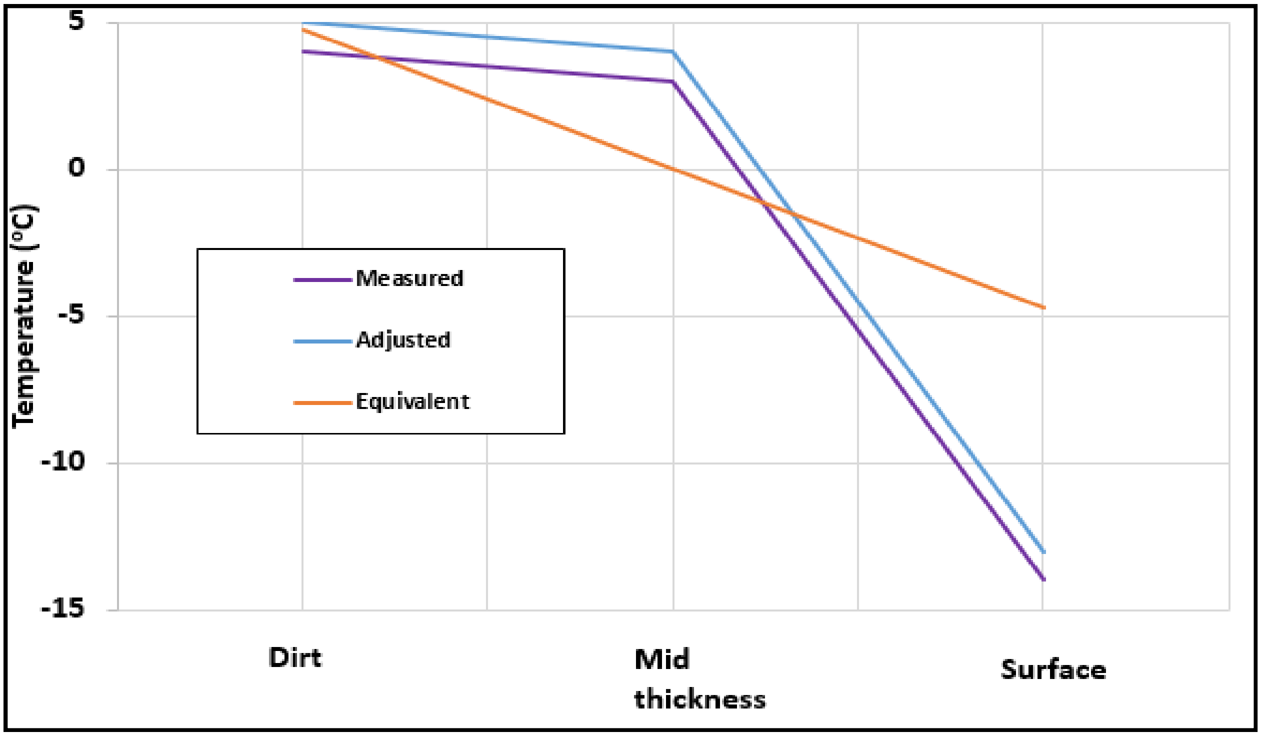

Figure 17. Calculated Equivalent Temperature Gradient

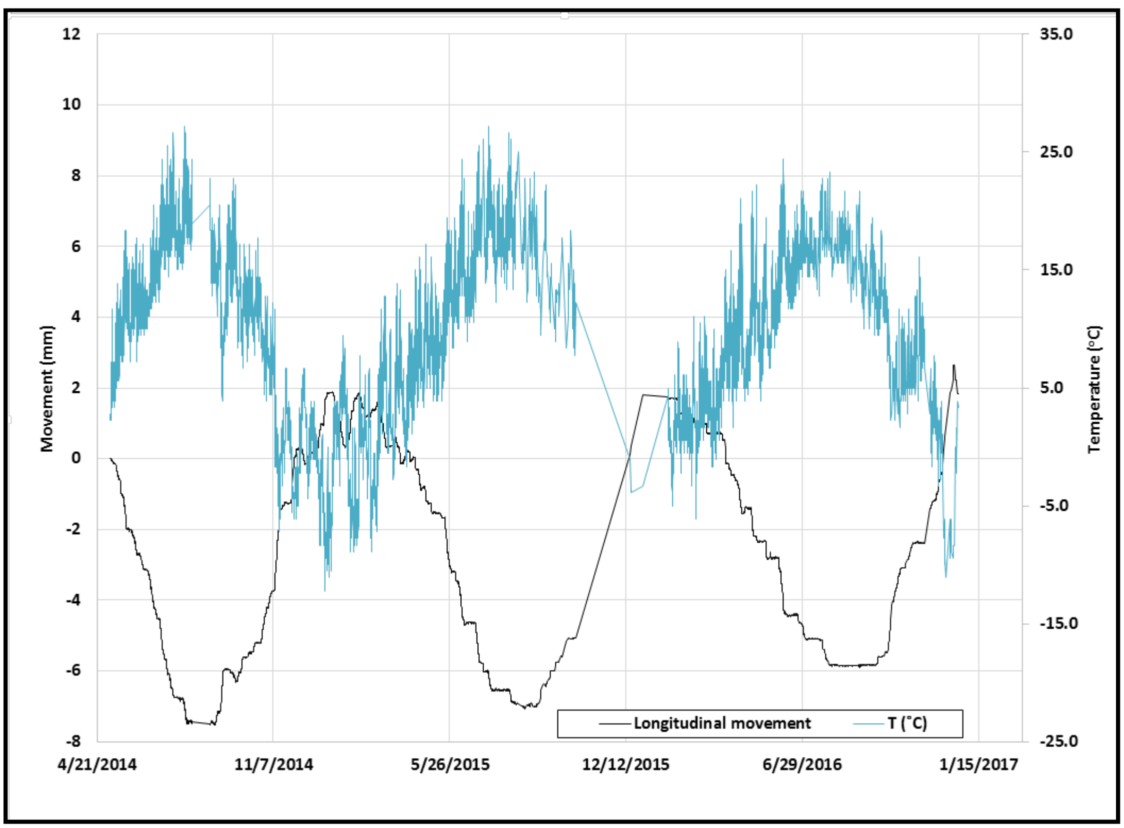

Figure 18. Longitudinal Movements