Temperature-based seepage monitoring of Bark Lake embankment dam

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ABSTRACT
A seepage monitoring system was put in place in 2003 by Ontario Power Generation/ Hydro Engineering Division as a means of detecting an early development of internal erosion through the foundation of the Bark Lake earthfill embankment dam. The system consists of an automated datalogger connected to a thermocouple array installed at depth in the downstream portion of the earthfill embankment dam to allow continuous monitoring of seepage. This method of seepage monitoring through temperature measurements is primarily based on the fact that increased seepage flow in zones with high permeabilities disturbs the internal temperatures of the dam foundation, which can be accurately measured through the installed thermocouple array. The internal measured temperature data are then reduced through various types of plots and are correlated to reservoir temperatures and headwater levels to locate zones with anomalous seepage rates.

RÉSUMÉ
Un système de suivi d'infiltration a été mis en place en 2003 par la division de l'ingénierie de l'Ontario Power Generation en vue de détecter un début de développement d'érosion interne dans le noyau de la digue de barrage en terre de Bark Lake. Le système se compose d'un enregistreur de données automatisé relié à une gamme de thermocouples installés en profondeur dans la partie aval de la digue de barrage ;ce qui permet un suivi continu des infiltrations. Cette méthode de suivi des infiltrations couplée de mesure de la température est fondée sur le fait que l'augmentation des flux d'infiltration dans les zones à forte perméabilités perturbe la température intérieure du barrage, ce qui peut être mesuré avec précision grâce à la gamme de thermocouples installée. Les mesures de température interne sont ensuite analysées et corrélées graphiquement à la température du réservoir et du niveau amont pour localiser les zones à taux d'infiltration anormaux.

1 INTRODUCTION

Ontario Power Generation (OPG) owns and operates over 240 dams across Ontario. OPG has a comprehensive dam safety program encompassing dam engineering, design reviews, emergency preparedness and surveillance and monitoring.

Dam performance parameters such as seepage, pressure and deformation are monitored through various types of instrumentation. Seepage is a primary parameter of concern for earthfill embankments since excessive seepage can lead to internal erosion, piping and potential dam failure. Conventional methods for on-going seepage monitoring can include: visual monitoring, seepage collection and measurement through downstream weirs and monitoring of internal pore water pressures. Some shortfalls of these methods are that they are either too focused (point-source within dam) or too broad (large section along toe of dam). Some geophysical methods exist that may be utilized to get a "snapshot" of overall seepage conditions, however these methods also have limitations and are not typically used for continuous monitoring.

An ideal seepage monitoring system is one that would have the potential to provide a broad spectrum of possible seepage occurring through a longitudinal "window" within the dam and its foundation. To that end, OPG has embarked on a trial monitoring program that uses thermocouple trees installed in vertical boreholes within an existing embankment structure. These thermocouple trees provide an array of temperature sensors which can be used to monitor temperature variations to provide an indication of seepage conditions within the embankment and its foundation. This paper provides a description of the embankment dam site, seepage/leakage/temperature monitoring system and the results obtained to date which illustrate the use of this technology to identify preferential seepage pathways.

2 DAM SITE

Bark Lake Control Dam is located on the Madawaska River at the outlet of Bark Lake and is approximately 11 km south west of the town of Barry's Bay, Ontario. The dam is used in regulating the headwaters for five downstream generating stations on the Madawaska River. It consists of a 108m long concrete gravity section and a 197m long earthfill embankment (Figure 1). The total length of the dam is approximately 305m with a maximum height above the bedrock foundation of 20m. The earthfill embankment section of the dam is constructed over pervious deposits of sand, gravel, cobbles and boulders and it consists of a central clay core, transition zones, granular shells and upstream and downstream riprap. The maximum height of the fill is about 13m which includes a freeboard allowance of approximately 2m (Figure 2). A seepage cutoff consisting of a concrete corewall and steel sheet piles keyed into the bedrock, for the initial 130m from the concrete wingwalls, prevents under-seepage through the pervious strata. This barrier is continued with the impervious earthfill core above the original ground surface. The construction of Bark Lake Control Dam was completed in 1942 by Ontario Hydro.

Given the existing measures and configuration of the dam seepage cutoff described above, also shown in Figure 3, there exist some zones that constitute preferential seepage/leakage pathways which may lead to internal erosion and piping through the foundation of the dam. These zones are a) the interface between the sheet piles and the bedrock where the sheet piles do not penetrate into the bedrock b) the interface between the sheet piles and the concrete corewall c) the sheet piles themselves due to the interlocks between the individual piles and d) any damaged section in the sheet piles such as unlocked sheets, tearing, splitting, etc, which could have been taken place during driving of the sheet piles. It should be noted that piping through the dam clay core is also possible; however, it is not addressed in this paper.

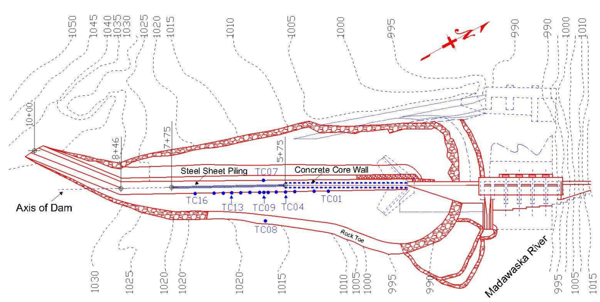

Figure 1: Plan View of Bark Lake Dam showing gravity section; earthfill embankment; concrete corewall; steel sheet piles; and locations of thermocouple trees.

Therefore, a seepage monitoring system based on temperature measurements was put in place in 2003 by Ontario Power Generation/Hydro Engineering Division to ensure the effectiveness of the seepage cutoff measures and to detect, at an early stage, any water percolating through the steel sheet piles or through any other vulnerable zone identified above.

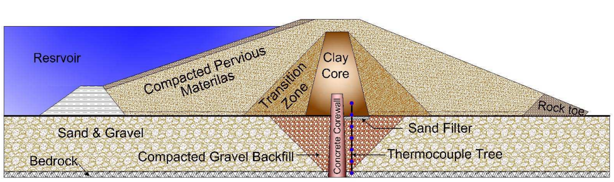

Figure 2: Cross Section of Bark Lake Embankment Dam passing through Concrete Corewall and showing a thermocouple tree for temperature measurements

3 SEEPAGE/LEAKAGE MONITORING SYSTEM

The seepage monitoring system at Bark Lake Dam basically consists of an automated datalogger connected to a series of thermocouples at depths in the downstream portion of the earth dam. A review of the geometry of Bark Lake Dam and consideration of the vulnerable zones identified above led to the selection of 16 monitoring thermocouple trees (TC 01 – TC 16) at depths below crest of dam between 35 to 65 feet in 5 foot increments over an approximately 223 foot length of the dam from Chainage 5+02ft to 7+25ft, see Figure 3. Each thermocouple tree is attached to an outside 1” diameter PVC casing and lowered into a 2” diameter PVC casing augered to bedrock.

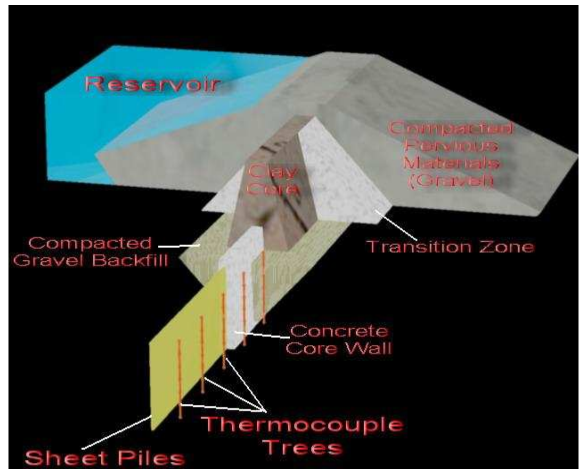

Figure 3: 3D Cross Sectional Perspective of Earth Dam showing various Components of Earth Dam; seepage cutoff measures; and thermocouple trees for temperature measurements

Fourteen (14) of the sixteen 2” diameter casing holes were installed along the downstream edge of the dam crest. One casing (TC 07, Chainage 6+10ft) was installed into the upstream side of the dam crest and one casing (TC 08, Chainage 6+10ft) was installed into the toe of the dam. These two casings along with TC 08 (Chainage 6+15ft; installed at the downstream edge of the dam crest) provide a cross sectional temperature profile through the dam. The bottom of the outside casing was left uncapped and the bottom six feet of the inside pipe was slotted to act as piezometers for these three holes. Water level measurements are taken to characterize the phreatic surface through the dam at this chainage. Measurement of reservoir temperature is also taken through an individual thermocouple immersed 45ft deep in the headpond adjacent to the concrete headworks. Temperature readings are recorded every 12 hours and stored in the datalogger then acquired on a regular basis for review and graphical analysis. Accuracy of temperature measurements is within ±0.3^{o}C.

4 BASICS OF TEMPERATURE MEASUREMENTS FOR LEAKAGE DETECTION THROUGH EMBANKMENT DAM

The internal thermal regime in an embankment dam is affected by different thermo-hydraulic processes; heat conduction, advection and radiation. However, given the short duration of diurnal heat pulse and the low value of the thermal conductivity of dry soil materials, the effect of atmospheric heat radiation is restricted only to a superficial depth of the embankment dam (less than 10m) and it is usually a small fraction of one degree centigrade and can be ignored (Bedmar and Araguas, 2002 and Johansson 1997). On the other hand, the heat conduction and advection are partially coupled processes (Johansson 1997) through which reservoir temperature is mainly transported into the dam body. These advective and conductive heat transports associated with reservoir water temperature perturb the thermal regime of the embankment dam and therefore can be used as means of leakage detection.

5 DATA INTERPRETATION AND ANALYSIS

Interpretation and analysis of collected temperature data for localization of leakage potential are done visually by different types of plots namely temperature depth profiles at specific chainage, longitudinal temperature profile along a specific depth and sectional temperature contours through the dam foundation. Utilizing different types of plots is advantageous in a sense that certain temperature anomalies are more pronounced in some types of plots than others.

Temperature data should be also viewed within the context of reservoir temperature and headwater level as these two pieces of information have significant effects on the measured temperature data.

Given the abundant volume of temperature data that have been collected twice a day since 2003, customized MATLAB macros were developed to expedite the visualization process. All produced plots of a specific type are compiled to produce a snippet so that changes in dam thermal field over the years can be viewed within a few minutes. It is important to note that sequential time-stepped visualization of the data reveals valuable information or anomalies that are not possible in still pictures.

5.1 Sectional Temperature Contours

Figure 4 shows a theoretical sectional temperature contour where no seepage or leakage water is perturbing the field temperature of the dam foundation. In this case, the dam foundation will be thermally stratified along its depth (Taniguchi et al. 1999). However, advective heat transport associated with reservoir water percolating through the dam foundation distorts its thermal stratification.

Figures 5 and 6 show some representative sectional temperature contours at two different dates. Shown in the figures are the measured reservoir temperature, date and time of measurements. Several interesting features can be identified in these contours. A temperature anomaly is identified along Ch 5+75ft between 50 and 65 ft which corresponds to a part of the interface between the concrete corewall and the steel sheet piles.

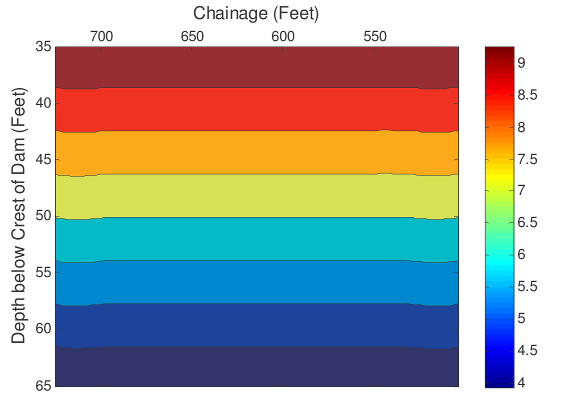

Figure 4: Theoretical Sectional Temperature Contour with no Seepage or Leakage Percolating through Dam Foundation- Dam Foundation is Thermally Stratified

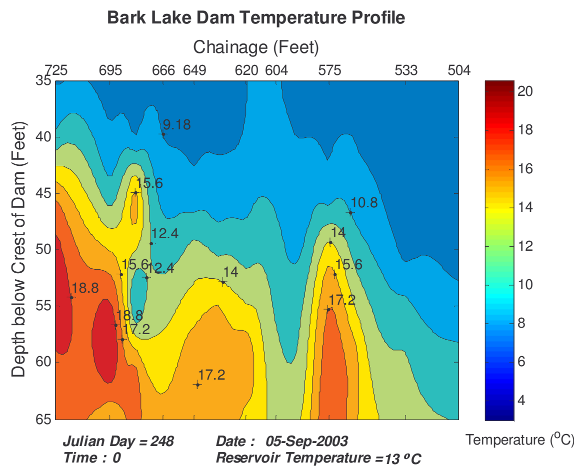

Figure 5: Sectional Temperature Contour through Dam Foundation during Summertime

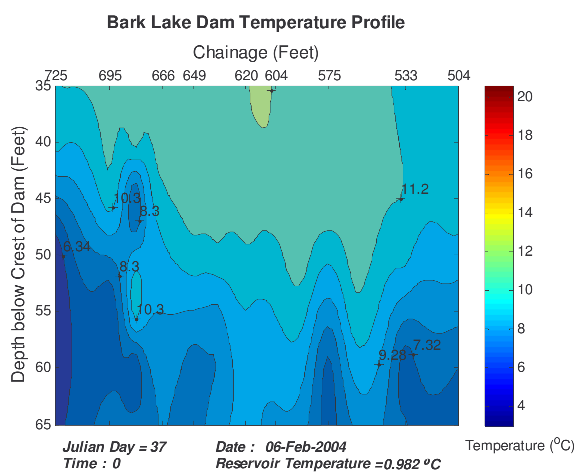

Figure 6: Sectional Temperature Contour through Dam Foundation during Wintertime

It is always important to correlate the temperature of the percolating water (temperature anomaly) to the reservoir vertical temperature profile so that depth at which the percolating waters infiltrate in the reservoir can be identified. There is a noticeable difference between the reservoir temperature and the temperature of the percolating water (anomaly) through Ch 5+75ft. This temperature difference is attributed to the fact that the point where the reservoir temperature is measured is far from the potential source of the water infiltrating the reservoir. Furthermore, the irregular topography of the original ground (Figure 1) further complicates the matter. Depth of headpond increases eastward toward the headworks ranging, during full reservoir operation, from 8ft at Ch 7+25ft to 50ft at the headworks where the temperature of reservoir water is measured. As a result of an increased reservoir depth near the headworks, the reservoir is likely to be thermally stratified (during summertime) and the shallow reservoir toward the west bank has a uniform temperature along its depth. Therefore, a plan is being devised to install a thermocouple tree in the headpond so that the reservoir vertical temperature profile can be obtained and consequently improved interpretations of temperature data achieved.

Other anomalies characterized as concentrated circles are also identified in the same contours at the following locations (Ch 6+95ft, 57ft); (Ch 6+81ft, 45ft); and (Ch 6+81ft, 55ft). These circles (anomalies) may be indications of concentrated seepage in the dam foundation through the sheet piles.

An anomaly along Ch 7+25ft is also identified between 50ft and 65ft. It is also clear that water percolating through the interface of the sheet piles and the bedrock between Ch 6+20ft and Ch 7+25ft is likely distorting the temperature field along the interface between 60ft and 65ft. It should be noted that these concentrated circular anomalies have different temperature suggesting that they may be linked to different sources in the reservoir.

5.2 Longitudinal Temperature Profiles

This type of plot can be utilized here to highlight the anomalies identified in the contour plots. Figures 7 to 13 show the longitudinal temperature profiles at different depths. Shown in the same figures is the reservoir temperature. The headwater level shown in Figure 7 also applies to the other longitudinal profiles.

Figure 7 reveals that temperature along chainages at 35ft depth is uniform. However, minor anomalies are identified. First it is readily seen that temperatures along Ch 5+04ft, Ch 5+33ft, and Ch 5+61ft are slightly lower than the rest and have the maximum temperature drift from the reservoir temperature. This might be explained by the presence of the concrete corewall along these chainages. Another identified anomaly is at Ch 6+15ft which has the smallest temperature drift from the reservoir temperature. This could be an indication of increased seepage at this location. This is also apparent in the contour plots shown above. There does not seem to be any anomaly along the interface between the concrete corewall and the steel sheet piles (Ch 5+75ft) at this depth.

At 40ft depth the temperature profile is somewhat uniform except for the large temperature drift at Ch 5+04ft and Ch 5+33ft due to the presence of the concrete corewall. In addition, the temperature drift at Ch 7+25ft is also different from the rest. This anomaly might be attributed to increased seepage through the sheet piles at this chainage.

At 45ft depth one additional anomaly is found at Ch 6+81ft. An interesting note is that the temperature in the dam at this chainage and depth is higher than the reservoir temperature. As noted above, the measured reservoir temperature might not be representative of the whole reservoir. In fact at Ch 6+95ft the headwater is very shallow (about 10ft) and therefore its temperature would be closer to atmospheric temperature which is probably higher than the measured reservoir temperature taken near the headworks at 45ft deep. This anomaly is also clearly pronounced in the contour above by the concentrated circle.

At 50ft depth a temperature anomaly is present along the interface between the concrete corewall and the steel sheet piles. In addition, other temperature anomalies are also found along Ch 6+81ft, Ch 6+95ft, and Ch 7+25ft. At depths of 55ft, 60ft, and 65ft the above identified temperature anomalies are again strongly pronounced in Figures 11, 12, and 13 which indicates that seepage rates are increasing with depth resulting in more pronounced temperature anomalies.

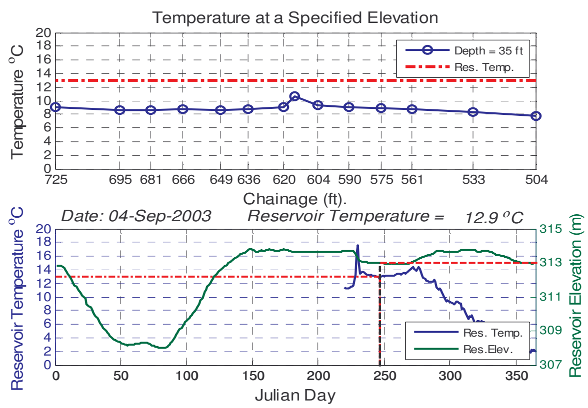

Figure 7: Longitudinal Temperature Profile at 35ft Deep in Dam Foundation

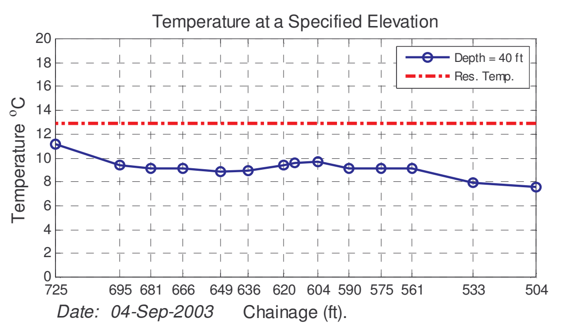

Figure 8: Longitudinal Temperature Profile at 40ft Deep in Dam Foundation

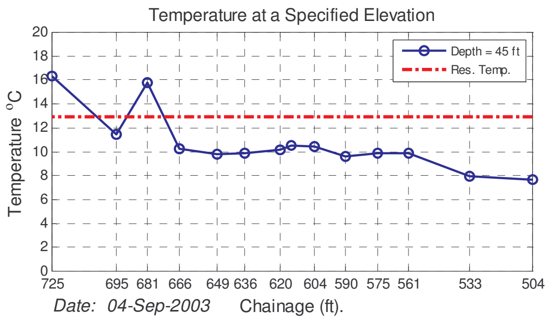

Figure 9: Longitudinal Temperature Profile at 45ft Deep in Dam Foundation

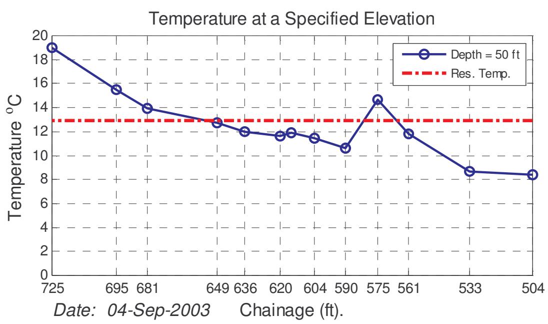

Figure 10: Longitudinal Temperature Profile at 50ft Deep in Dam Foundation

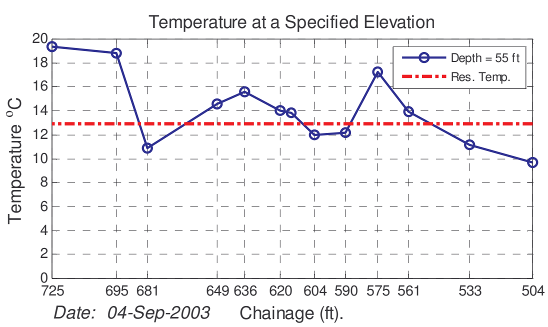

Figure 11: Longitudinal Temperature Profile at 55ft Deep in Dam Foundation

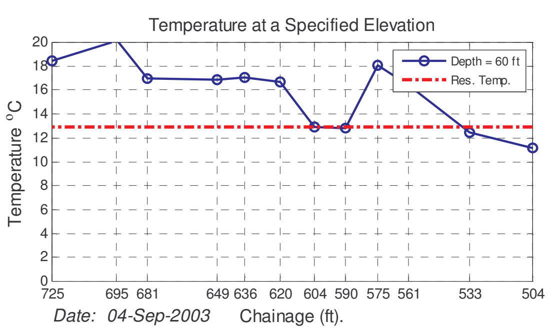

Figure 12: Longitudinal Temperature Profile at 60ft Deep in Dam Foundation

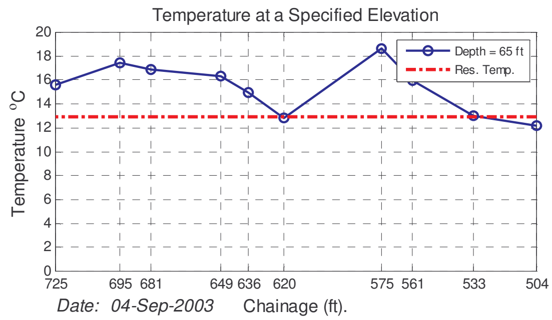

Figure 13: Longitudinal Temperature Profile at 65ft Deep in Dam Foundation

5.3 Temperature Depth Profiles

Generally, a temperature depth profile in the geothermal zone, which occurs below a depth of around 10m, has a constant gradient with depth except when perturbed by groundwater flow (Anderson 2005). Figures 14 to 26 show the temperature depth profiles for the thermocouple trees at between 35 and 65ft depths for different dates during the year of 2007. A temperature depth profile during summertime is characterized by an upward concave curve as opposed to an upward convex curve during wintertime. This observation was arrived at after examining several years of temperature depth profiles.

The temperature depth profile at Ch 5+04ft shows a slightly increased seepage between depths 55 and 65ft. This is identified by the constant temperature stretch between 55 and 65ft. This constant stretch may not be detectable at all dates. The temperature depth profile at Ch 5+33ft shown in Figure 15 also indicates an anomalous seepage zone between 60ft and 65ft, which clearly show during summertime.

It should be emphasized that temperature depth profiles be viewed during several dates, preferably summertime and winter time, as anomalies may not show all the time as headwater level varies over the year.

An increased seepage at depth of 45ft is identified in the temperature depth profile at Ch 5+61ft shown in Figure 16.

At Ch 5+75ft a constant temperature stretch (during wintertime) between 50ft to 65ft is an indication of increased seepage along the interface between the steel sheet piles and the concrete corewall (Figure 17). This observation is in keeping with the anomalous zone identified at this location in the sectional contour plots shown above.

The temperature depth profile at Ch 5+90ft (Figure 18) has a constant temperature stretch (summertime) between depths of 35ft and 45ft and 55-65ft which indicate increased seepage flows at these two locations.

Another anomalous zone between 45ft and 65ft is also indicated (wintertime) in the temperature depth profiles at Ch 6+04ft shown in Figure 19.

At Ch 6+15ft the temperature depth profile is shown in Figure 20 which indicates two anomalous seepage zones between depths of 35-40ft and 50ft and 55ft.

Figure 21 shows the temperature depth profile at Ch 6+20ft with an anomalous seepage zone between 55 and

65ft detected in June 21, 2007. The temperature depth profile at Ch 6+36ft shown in Figure 22 indicates an anomalous seepage zone between 55ft and 60ft.

Figure 23 shows the temperature depth profile at Ch 6+49ft which indicates the anomalous zone between 55ft and 65ft with an increased seepage at 60ft.

Two points with concentrated seepage are detected in the temperature depth profile of Ch 6+81ft shown in Figure 24. These two points have also been detected in the sectional contour plots shown above at 45ft and 55ft.

At Ch 6+95ft the temperature depth profile shown in Figure 25 indicates a concentrated seepage at depth of 55ft and an anomalous seepage zone between 50-65ft.

Figure 26 shows the temperature depth profile at Ch 7+25ft which also indicates a concentrated seepage at depth 50ft which may result in an anomalous zone between depth of 55ft and 65ft.

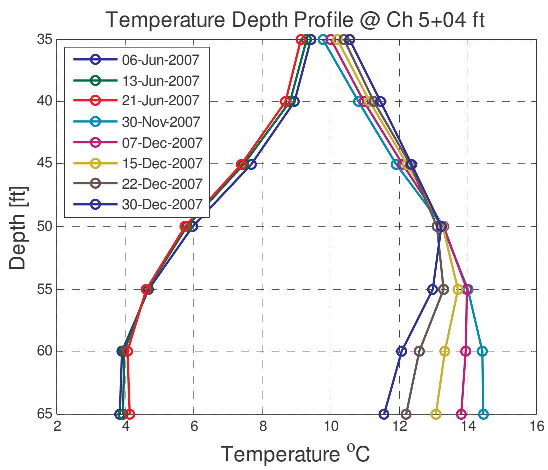

Figure 14: Temperature Depth Profile @ Ch 5+04ft

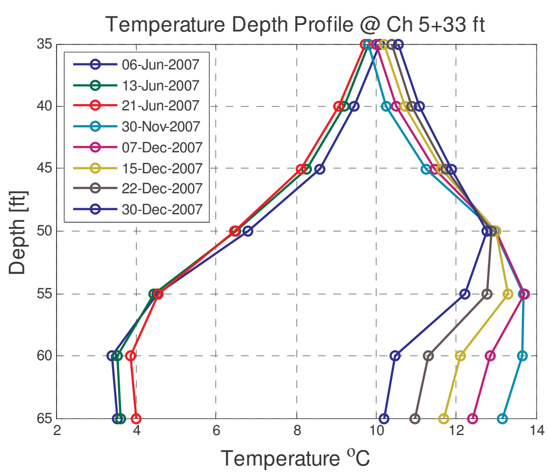

Figure 15: Temperature Depth Profile @ Ch 5+33ft

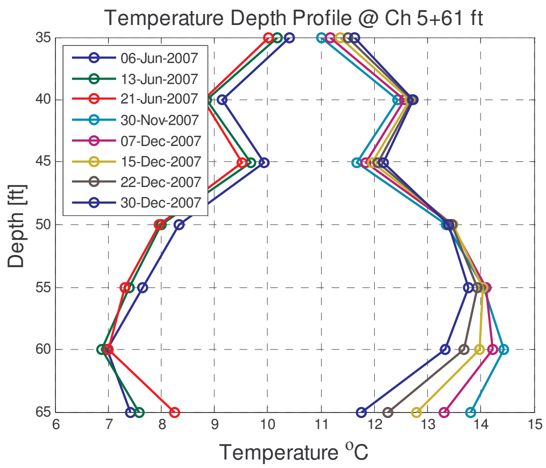

Figure 16: Temperature Depth Profile @ Ch 5+61ft

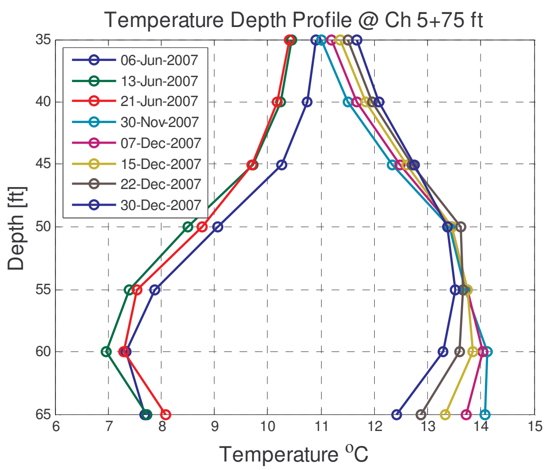

Figure 17: Temperature Depth Profile @ Ch 5+75ft

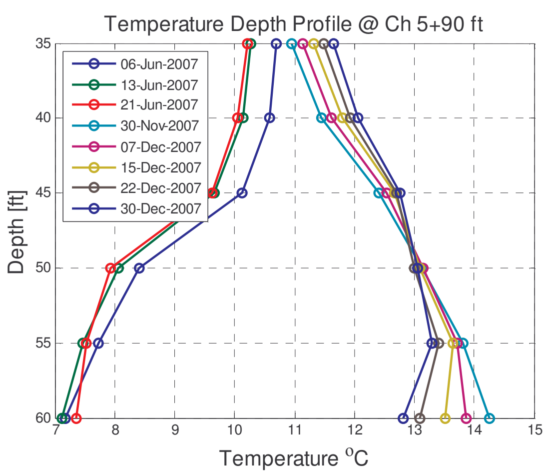

Figure 18: Temperature Depth Profile @ Ch 5+90ft

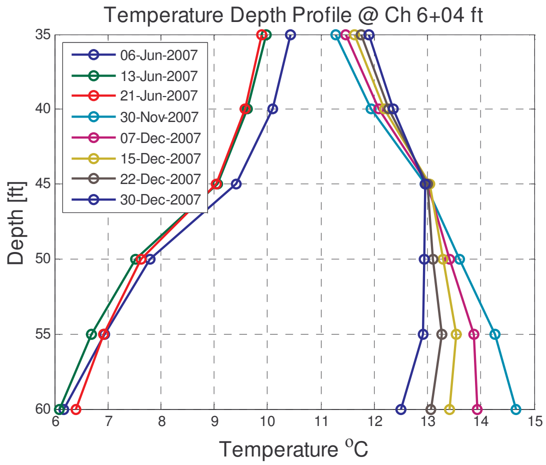

Figure 19: Temperature Depth Profile @ Ch 6+04ft

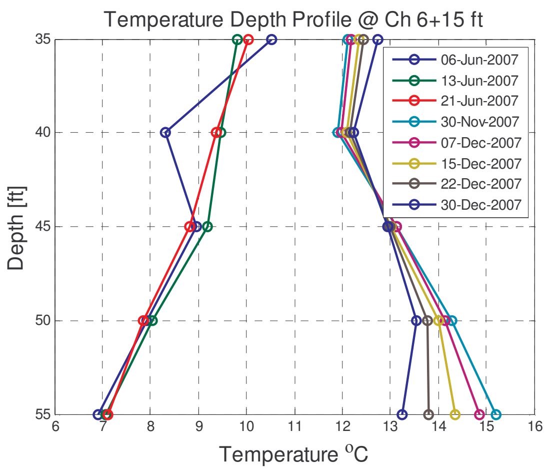

Figure 20: Temperature Depth Profile @ Ch 6+15ft

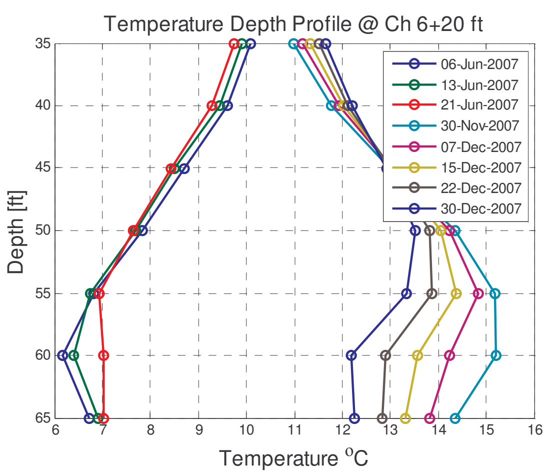

Figure 21: Temperature Depth Profile @ Ch 6+20ft

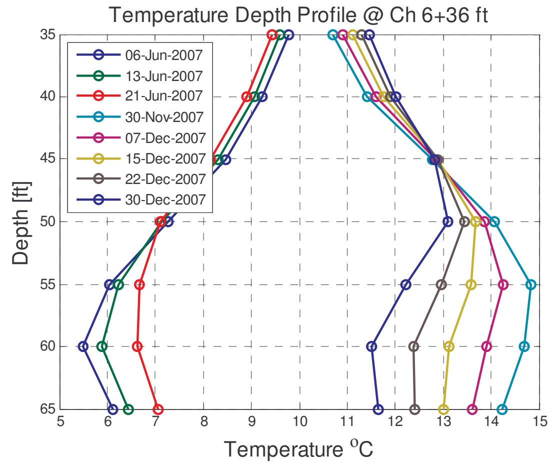

Figure 22: Temperature Depth Profile @ Ch 6+36ft

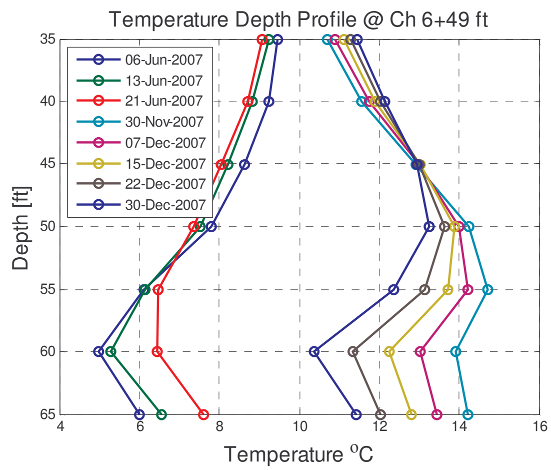

Figure 23: Temperature Depth Profile @ Ch 6+49ft

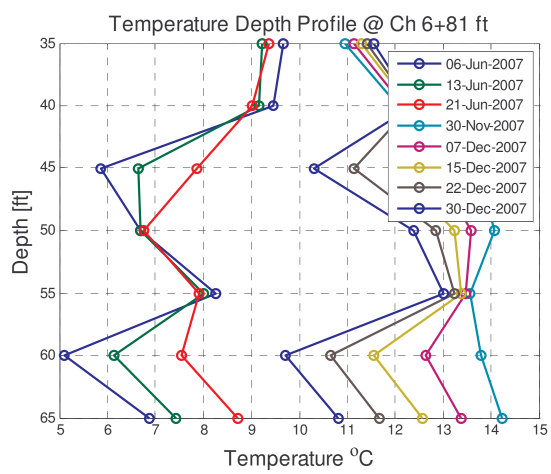

Figure 24: Temperature Depth Profile @ Ch 6+81ft

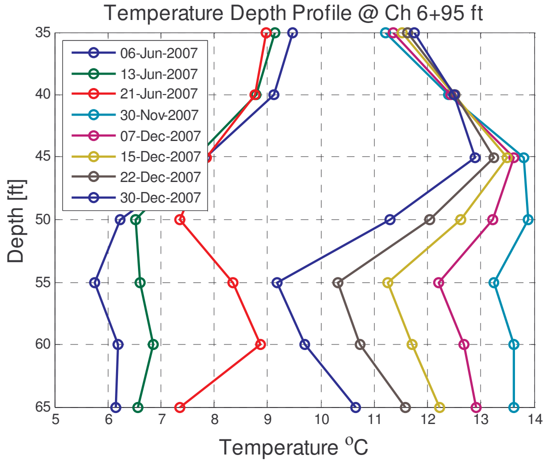

Figure 25: Temperature Depth Profile @ Ch 6+95ft

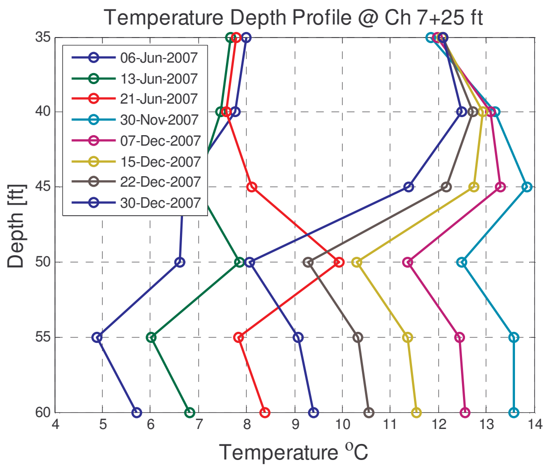

Figure 26: Temperature Depth Profile @ Ch 7+25ft

6 CONCLUSIONS

The temperature plots presented in this paper show that temperature measurement as a form of seepage monitoring has great potential. Through the data obtained to date, correlations can be made between potential seepage zones identified in the plots and actual features within the dam foundation which include: the interface between steel sheet piling and foundation bedrock; the interface between steel sheet pile and a concrete corewall; and any potential damage zones or anomalies in the dam foundation or sheet piling.

The contact interface between the steel sheet piles and the bedrock does not seem to be fully watertight. The anomalous temperature data along the interface apparent in the temperature contour plots and the constant temperature stretches between 50ft and 65ft are in keeping with this conclusion. This conclusion is also reinforced in the longitudinal temperature plots.

The interface between the steel sheet piles and the concrete corewall has a section with high permeability between depths of 50ft and 65ft. This conclusion is readily evident in the temperature contour plots.

Potential damaged sections in the steel sheet piles have been identified at the following locations: (Ch 6+95ft, 57ft); (Ch 6+81ft, 45ft); (Ch 6+81ft, 55ft); and (Ch 7+25', between 50ft and 65ft). These sections are characterized as concentrated circles in the temperature contour plots. The differences in temperature anomalies corresponding to these damaged sections suggest that the anomalies are caused by different sources of reservoir water infiltrating the dam at different locations (depths). However, these locations have not yet been localized as the reservoir vertical temperature profile is not currently known. Therefore, a plan is being developed to profile the vertical temperature of the reservoir.

A temperature depth profile during summertime is characterized by an upward concave curve as opposed to an upward convex curve during wintertime.

As headwater level fluctuates throughout the year, seepage or leakage rates vary accordingly. When the headpond is at its lowest level before the spring freshet, the rate of percolating water through some sections of the embankment dam, particularly towards the west end, might be too small to cause any temperature anomalies that stand out in the temperature plots. Therefore, sequential time-stepped viewing of these plots at various dates is essential in identifying these anomalies. This was very clear in the temperature depth profiles presented above where some constant stretches of temperature were only present in some dates.

The use of vertically installed arrays of thermocouples is beneficial because it allows for: the installation of additional arrays to focus on identified seepage anomalies; the removal and maintenance/repair of the arrays; and decommissioning of the arrays and/or re-use of the installed casings as observation wells.

Ontario Power Generation will continue to utilize this method of seepage monitoring as part of its comprehensive dam monitoring and visual surveillance techniques. Potential improvements to the existing temperature monitoring system include additional headwater temperature profile data and additional piezometric measurements within the thermocouple array so an increased understanding of seepage/ temperature behaviour is possible.

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