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FIELD CONDITION MONITORING OF WATER MAINS IN THE CANADIAN PRAIRIES

Tariq Saleem Chaudry
University of Manitoba, Canada

Catalin Gheorghiu
University of Manitoba, Canada

Yafei Hu
CSIR National Research Council, Canada

Abstract

Water distribution systems are gradually deteriorating due to aging, operational stresses and external environmental conditions. This deterioration has resulted in increased operation and maintenance costs and a reduction in the quality of both service and water supplied to customers. There is a need for a clear understanding of the behaviour of water mains under various conditions so that municipalities can manage their water distribution systems efficiently.
In order to understand soil behaviour and pipe-soil interaction under operating conditions, a field monitoring project has been set up. A section of asbestos cement (AC) pipe has been instrumented for the purpose of monitoring the performance of water mains in an older area of the City of Regina where frequent pipe breakage has been observed in recent years. The instrumentation includes sensors for monitoring the longitudinal and circumferential strains along the pipe section, pipe displacement, soil moisture content, soil pressure, and pipe and soil temperatures at different depths. Data from this field monitoring system will serve as a basis for research on the failure mechanisms and performance of AC water mains in the expansive clay soil conditions of the Prairies. The paper presents analysis of the measurements taken from strain and temperature sensors during the initial months of installation (September, 2006 – January, 2007). Preliminary results indicate that the pipe experienced no significant flexural strains. The temperature drop decreases with the increasing depth of the trench.

This project is unique in the sense that it is the first Intelligent Sensing for Innovative Structures (ISIS) application of monitoring water mains using fibre-optic sensors (FOS), a joint project with NRC IRC’s Centre for Sustainable Infrastructure Research, Regina, Canada.

INTRODUCTION

The City of Regina has two-thirds, that is approximately 531 km, of its water mains made up of asbestos cement (AC). These pipes have been experiencing more and more failures in the recent years and account for most of the water main breaks in the city. To ensure that the City can manage its water distribution network in a cost effective, reliable and sustainable manner, it is essential that a clear understanding be developed of AC pipe failure conditions and mechanisms.

A recent study [1] investigated the breakage pattern of the AC water mains for the period 1980-2004 in the City of Regina to assess the conditions and identify factors that influence the breakage of these water mains. It was observed that the pipe age, diameter, climate, soil conditions, construction and repair methods have all contributed to the pipe failures with climate and soil conditions being the two critical factors. Peaks in water main failures have been observed during the extreme dry and cold seasons. The observed monthly break pattern during the 25-year period was similar to that of Winnipeg where similar soil conditions exist [2].

Another work [3] analyzed the pipe breakage data of cast iron (CI) and AC water mains in the City of Winnipeg for the period 1948-1953 and observed that the monthly number of circumferential failures had a cyclic pattern with peaks occurring in September and January. The circumferential breakage pattern was compared with the monthly mean temperatures, precipitation and approximate depth of snow cover in the City of Winnipeg and a close correlation with seasonal climate changes was observed. It was suggested that the high swelling–shrinkage potential of soil in this area has a significant impact on these failures. Three test installations consisting of CI and AC mains were instrumented to monitor the pipe movement. Upward displacement was observed during the investigation and the maximum differential movement along the buried pipe was 20 mm in all the three test installations. Such movements induce flexural stresses in the pipe, potentially leading to circumferential failures or joint failures, especially in small diameter mains [1].

A broader study [4] analyzed data from 4 water authorities with inventory of AC pipes, one with clay soil and the other three in sand gravel conditions. It was observed that the distribution of water main failures was fairly random, during the year, in the areas with sand gravel whereas most of the failures in areas of predominantly clay soil occurred during the dry summer months. Two peaks in the annual failure rate were observed in the period from 1952 to 1982 and they corresponded to two hot summers with long dry periods, indicating higher shrinkage. The high occurrence (over 97%) of circumferential failures and the large proportion of failures of small diameter mains (over 98% being 75, 100 and 150 mm) suggests that circumferential failures caused by high flexural stresses induced by soil movement around the pipe prove detrimental for small diameter AC mains [1].

It can be inferred from the preceding discussion that for pipes buried in expansive soils, the occurrence of water main failures has close correlation with the variation in soil moisture content during extreme climate conditions. Montmorillonite clay with high swelling/shrinkage characteristics is dominant in the City of Regina. Reduction of soil moisture in dry summer seasons results in shrinkage of cohesive soil. Shrinkage of soil is also observed in winter season. This phenomenon is believed to be caused by the progressive freezing of the water in surface soil, which draws pore water from lower depths to form ice lenses [5]. As a result of less percolation of surface water during winter season, the reduced moisture content at lower depths causes shrinkage of soil. The changes in soil volume with the fluctuation in soil moisture result in soil movement. The movement of soil around the water mains results in flexural stresses through different mechanisms, such as non-uniform bedding support or differential settlement.

In order to better understand the soil’s behaviour and corresponding responses of water mains under expansive soil conditions, a field instrumentation and monitoring system has been set up to continuously monitor the performance of polyvinyl chloride (PVC) and AC pipe sections. The preliminary strains and temperature measurements obtained from the sensors installed on the AC pipe section are discussed here whereas the results from the PVC pipe section have been published elsewhere [2].

FIELD INSTALLATION

A section of AC pipe was installed in a residential area of the City of Regina. The selection of location was based on a number of factors including the number of breaks that occurred during the past five years, access to power source, and space for putting up the instrumentation enclosure.

Trench Excavation and Backfill

Field installation was carried out between September 11, 2006 and September 15, 2006. A trench, 2.5-m-wide, 5.9-m-long and 2.6-m-deep was excavated (Figure 1) and the existing AC pipe section, which was 2.2 m below the ground surface, was removed. Installation of instrumented section of pipe and sensors was carried out at different levels below the ground. The external instrumentation box is shown in Figure 2.

Sand provided by the City of Regina was used as backfill material for the haunch and bedding areas throughout the trench. Mixed Concrete, a blend of recycled crushed concrete and subbase gravel with a ratio of 2:1 by weight was used from the pipe haunch up to 150 mm above the top of the pipe. The trench was backfilled and compacted up to the pavement level using several 150-mm-thick native soil layers according to the specifications recommended in [6].

Figure 1. Installation of Instrumented AC Pipe Section   Figure 2: Data Acquisition System.

Replacement of Existing Pipe Section

The existing pipe was 150 mm diameter (Class 150) AC pipe originally installed in 1961. The new instrumented AC pipe had the dimensions as the original one (Table 1). The new AC pipe was connected to other AC pipes of the water mains system using robars [7].

Table 1: Asbestos Cement Pipe Dimensions

Parameter	Pipe Dimensions
Nominal Diameter (mm)	150
Outer Diameter (mm)	183
Inside Diameter (mm)	146
Length (m)	4.0

Soil Conditions

The soil at the site consists of highly plastic glacial lake lacustrine clay from the surface to a depth of 8.5 m with glacial till beneath it. The soil conditions at the site were assessed in four sample boreholes. One borehole was 800-mm south of centerline of the pipe and the other three were about 2, 5, and 12.1-m north of the pipe respectively.

MONITORING SYSTEM

A monitoring system has been installed to provide a minimum of two years of data, which is serving as a basis in the on-going study on failure mechanisms of AC pipes. Layout of the sensors on the AC pipe is shown in Figure 3. The sensing system includes:

- 24 electrical strain gauges (ESG) on the exterior pipe surface for measuring longitudinal and circumferential strains
- 2 long gauges (LG) for measurement of circumferential strains
- 8 Fibre Bragg Grating (FBG) fibre optic sensor (FOS) for measurement of longitudinal and circumferential strains
- 25 thermocouples on the pipe surface and in the surrounding backfill material for temperature measurements
- 4 pressure cells at the pipe level to measure changes to soil pressure
- 20 Time Domain Reflectometry probes (TDR) for measurement of moisture content in the backfill
- 2 extensometers to measure vertical displacement of the soil
- 16 Fredlund Thermal Conductivity sensors for measuring soil suction and temperature, and
- 2 vibrating wire piezometers for measuring water pressure inside and outside the pipe.

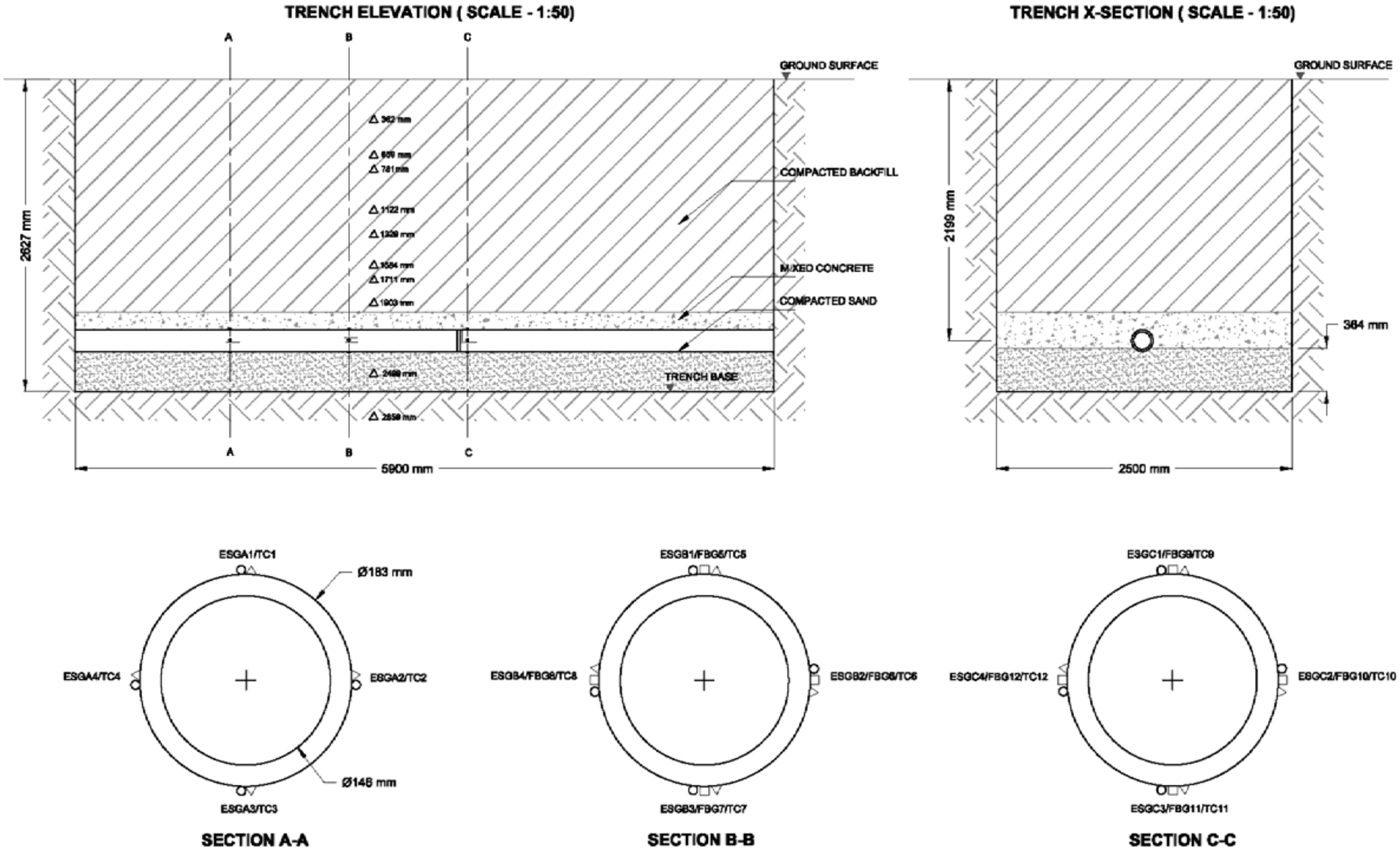
Strain Measurement

Electrical strain gauges (ESG) were installed to measure the deformation response of the AC pipe. Micro-Measurements general-purpose WK-06-250TM-350 ESG were selected for this purpose. Three sets of strain gauges were installed equally spaced along the pipe length. Each set consisted of four pairs of gauges, one on the top of the pipe, one on the bottom of the pipe and the other two on the springline. Each pair of strain gauges is providing both longitudinal and circumferential strain readings.

Three dummy strain gauges mounted on small rectangular coupons prepared from AC pipe of identical specifications together with three thermocouples, one for each dummy strain gauge, were placed in the backfill as close as possible to the ESG-instrumented cross-sections. The deformation due to temperature alone is measured by the dummy strain gauges and is used to correct the deformation measured by the strain gauges on the pipe surface.

Fibre-Optic Sensors

Ten *fibre optic sensors* (FOS) were installed to measure strain in the pipe section. Two 1-m long-gauge sensors were placed around the pipe at Section C-C (Figure 3) to measure hoop strains in the AC pipe. Two sets, consisting of 4 FBGs were installed at the Section B-B and Section C-C next to the ESG. FBGs at the Section B-B were aligned to measure the longitudinal strains, whereas at the Section C-C, these were aligned to measure circumferential strains.



INSTRUMENTATION LAYOUT		
SECTION A-A	SECTION B-B	SECTION C-C
4 THERMOCOUPLES	4 THERMOCOUPLES	4 THERMOCOUPLES
8 ESG	8 ESG	8 ESG
	4 FBG	4 FBG
		2 LONG GAUGES

LEGEND	
□	FIBRE BRAGG GRATING
○	ELECTRICAL STRAIN GAUGE
△	THERMOCOUPLE

Figure 3. Asbestos Cement Pipe Instrumentation Layout.

Temperature Measurement

Thermocouples were placed on the surface of the pipe adjacent to the strain gauges, in the backfill, as well as on the surface of the pipe coupons. Twenty five type T thermocouples were installed during the field work: 12 thermocouples on the exterior pipe surface, 3 thermocouples adjacent to dummy strain gauges, and 10 thermocouples in the backfill.

Data Acquisition System (DAQ)

A CR1000-55 data-logging system from Campbell Scientific Inc. was installed to collect the data from the electrical strain gauges. The data-logging equipment is housed on-site in a metal instrumentation box installed 1.2-m north of the trench (Figure 2). Readings are recorded hourly from these sensors. The FOS DAQ consists of IDERS SHM 5100-A for the FBG sensor, and FOX-TEK FTI-3300 FT for the long-gauge strain sensors. FOS readings are taken periodically every other month for a period of approximately 1 hour.

RESULTS AND DISCUSSION

The measurements obtained from the ESG, FOS, and thermocouples are discussed in the following. Preliminary FBG results are presented herein. The first set of FOS readings was recorded on January 23, 2007. First, analysis of ESG readings from September – January 2007 is presented followed by readings taken on January 23, 2007 for a 24-hour period. The strain readings have been corrected for temperature and include the deformation due to stresses and temperature. A comparison between the relative change in ESG and FBG measurements is presented for one-hour period on January 23, 2007.

Electrical Strain Readings between September 06, 2006 and January 31, 2007

The longitudinal strains recorded at the midspan, Section B-B of the pipe are shown in Figure 4. The strain curves are obtained by plotting hourly strain data from two days in a month, the 15th and the last day of the month. A straight line joins the two days together assuming a linear variation. Spikes are observed which can be correlated with daily variations in water pressure. The amplitude of spikes can be seen decreasing with time possibly as a result of backfill soil compaction. The longitudinal strains at the top (ESGB1) and bottom (ESGB3) are almost identical indicating that the pipe is experiencing mainly axial stresses without significant bending stresses. Strain gradually increased to reach a peak around mid November, and then decreased to a plateau at about 0.15% (ESGB1&ESGB3) and 0.05% (ESGB2&ESGB4) by mid December 2006. The longitudinal strains observed at the other cross-sections along the pipe show a similar pattern.

Figure 5 shows the measured circumferential strains at the midspan. Similar to the longitudinal strains, the pipe experienced a significant increase in circumferential strain until mid November and then has attained steady state in the range 0.05 and 0.1%. Spikes similar to that of longitudinal strains are notable. The decrease in spikes’ magnitude is suggesting that the backfill soil has compacted with time providing better confinement to the pipe. The circumferential strains at the other cross-sections show a similar pattern.

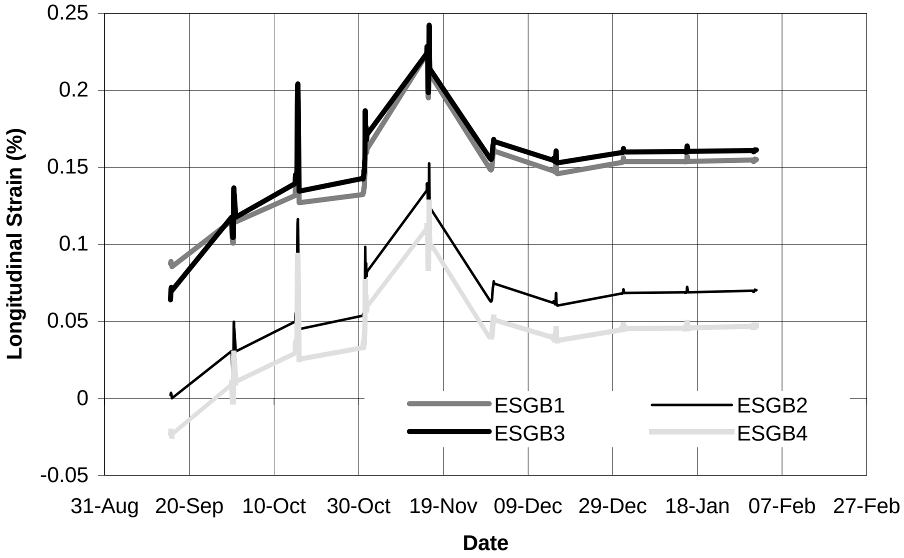


Figure 4. Longitudinal Strains versus Time at Section B-B.

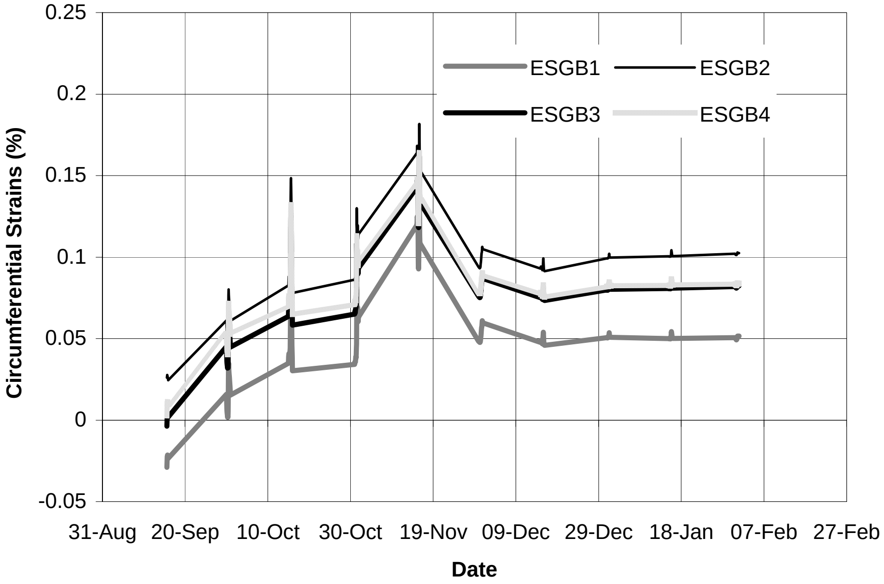


Figure 5. Circumferential Strains versus Time at Section B-B.

Electrical Strain Readings for a 24 Hour Period (January 23, 2007)

Figures 6 and 7 show the variation of the longitudinal and circumferential strain at Section B-B during a 24-hour period on January 23, 2007. A strain value is recorded every hour for all gauges. From midnight to about 11h00, longitudinal strain readings are constant. A gradual increase is noticed to reach a peak at 15h00. At that particular time, water pressure in the network reached a maximum of 421 kPa, 21 kPa higher than nominal water pressure. From this moment on, a gradual decrease is noted until midnight. This change in strain can be related to the change in water pressure throughout the network. Similar behaviour is observed for the circumferential strains (Figure 7), and the other instrumented cross-sections.

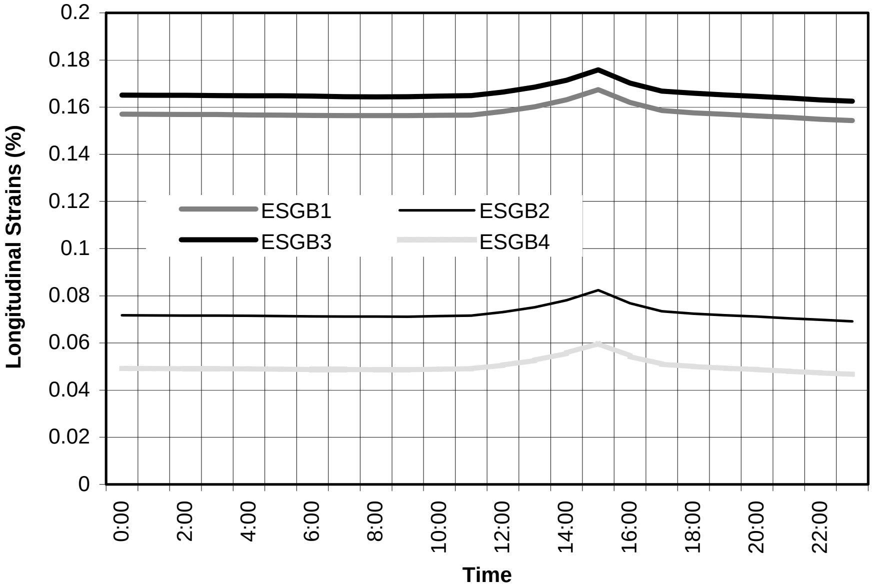


Figure 6. Hourly Variation of Longitudinal Strains at Section B-B on January 23, 2007.

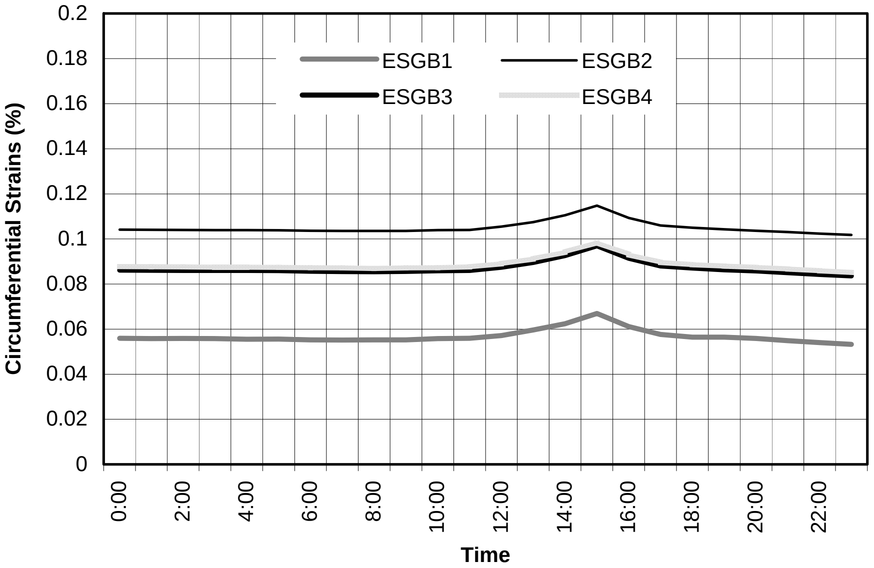


Figure 7. Hourly Variation of Circumferential Strains at Section B-B on January 23, 2007.

Electrical and FOS Strain Readings for a One Hour Period

Figure 8 shows relative longitudinal strains recorded on 23 January 2007 for an hour by the ESG and FOS installed at Section B-B. Since ESG strain measurement is taken every hour, two values are joined to form the straight lines for ESGB1 and ESGB2. For the FBG sensors, a higher sampling rate was used. The two instruments measure similar strains, and in this case the difference of 0.005% is insignificant. The relative change of strain values measured by ESG and FOS will be observed during the monitoring process.

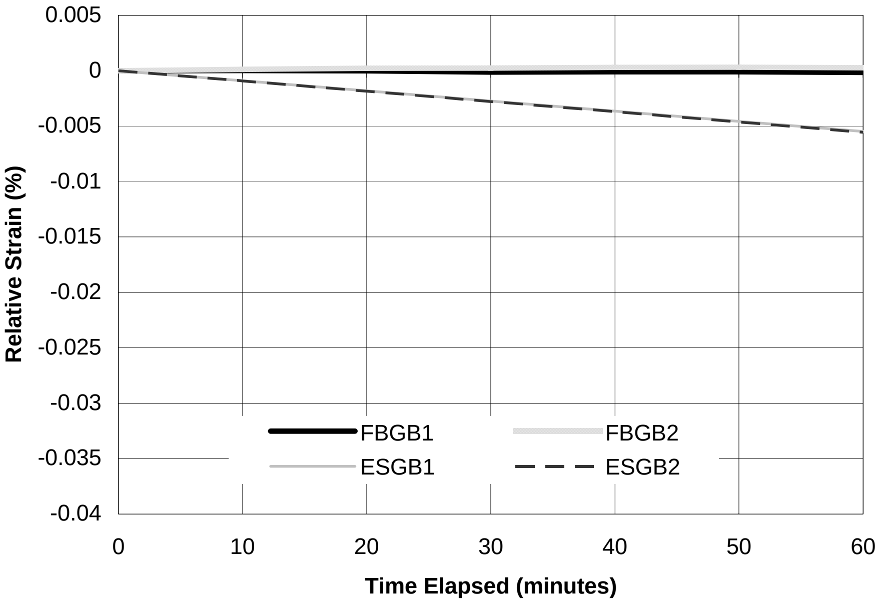


Figure 8. Comparison of FBG and ESG Strains at Section B-B on January 23, 2007 (15h00-16h00).

Temperature Readings

Figure 9 shows the average temperatures recorded from some of the thermocouples located at different depths throughout the trench between September 2006 and January 2007. The results show high variation in temperatures closer to the ground surface. At pipe level and below, the temperature dropped at a fairly stable rate but did not go past the freezing point.

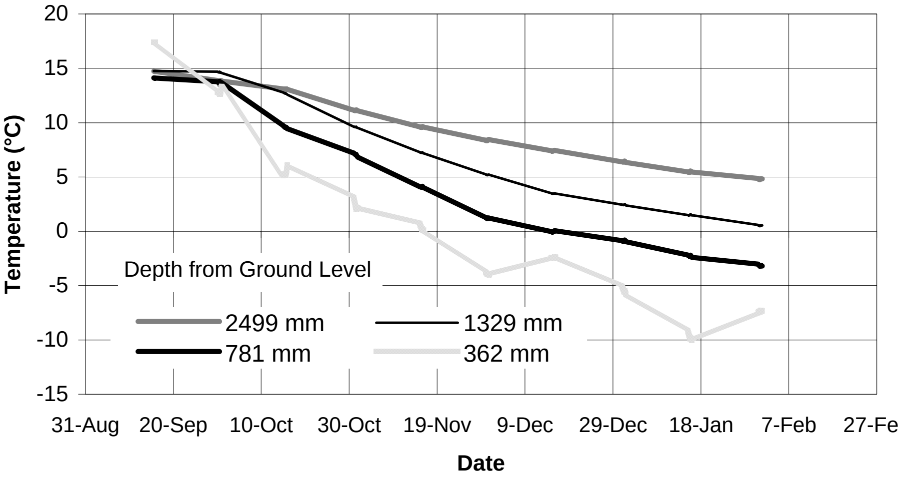


Figure 9. Temperature versus Time at Different Levels in Trench.

CONCLUSION

The instrumented AC pipe section was installed successfully in the City of Regina water mains distribution network as a part of ongoing research on the failure mechanisms and behaviour of PVC and AC water mains. This pipe monitoring installation is the second project within the City, and is the first Canadian FOS application for water mains monitoring. For the current installation, preliminary strain and temperature measurements up to date were presented. Soil temperature readings show seasonal variations that were to be expected. Strain data varied significantly especially immediately after the installation. This initial strain variation has been mainly caused by backfill soil compaction. Daily strain variation was noticed for both longitudinal and circumferential strain. The change is mainly caused by the daily variation of water pressure in the distribution network. The amplitude of the change diminishes with time as the backfill soil compacts with time, thus providing better confinement to the pipe. The collected data from the sensors will be utilized in developing soil-pipe interaction models of PVC and AC pipes in expansive clay soil conditions. The field monitoring of water mains together with planned laboratory and theoretical studies will significantly contribute towards a better understanding of water mains behaviour in harsh environmental conditions.

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