NRC Publications Archive Archives des publications du CNRC

Analysis of soil conditions and pipe behaviour at a field site

Hu, Y.; Vu, H. Q.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

For the publisher's version, please access the DOI link below. / Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

Publisher's version / Version de l'éditeur:

<https://doi.org/10.1139/t11-010>

Canadian Geotechnical Journal, 48, 6, pp. 847-866, 2011-05-27

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=d90aa54e-05e8-46e0-89db-d9dfe8f0f61a>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=d90aa54e-05e8-46e0-89db-d9dfe8f0f61a>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

<http://www.nrc-cnrc.gc.ca/irc>

Analysis of soil conditions and pipe behaviour at a field site

NRCC-54465

Hu, Y.; Vu, H.Q.

July 2011

A version of this document is published in / Une version de ce document se trouve dans:
Geotechnical Journal, 48, (6), pp. 847-866, May-27-11, DOI: [10.1139/t11-010](https://doi.org/10.1139/t11-010)

The material in this document is covered by the provisions of the Copyright Act, by Canadian laws, policies, regulations and international agreements. Such provisions serve to identify the information source and, in specific instances, to prohibit reproduction of materials without written permission. For more information visit <http://laws.justice.gc.ca/en/showtdm/cs/C-42>

Les renseignements dans ce document sont protégés par la Loi sur le droit d'auteur, par les lois, les politiques et les règlements du Canada et des accords internationaux. Ces dispositions permettent d'identifier la source de l'information et, dans certains cas, d'interdire la copie de documents sans permission écrite. Pour obtenir de plus amples renseignements : <http://lois.justice.gc.ca/fr/showtdm/cs/C-42>

National Research
Council Canada

Conseil national
de recherches Canada

Canada

Analysis of Soil Conditions and Pipe Behaviour at a Field Site

Yafei Hu*

Centre for Sustainable Infrastructure Research

Institute for Research in Construction, National Research Council Canada

Suite 301, 6 Research Drive

Regina, SK, Canada S4S 7J7

Phone: (306) 780-5432

Fax: (306) 780-3421

Email: yafei.hu@nrc-cnrc.gc.ca

and

Hung Q. Vu

Golder Associates Ltd., 1721 8th Street East

Saskatoon, SK, Canada S7N 0T4

Phone: (306) 667-1284

Fax: (306) 665-3342

Email: hung_vu@golder.com

*Corresponding author

Analysis of Soil Conditions and Pipe Behaviour at a Field Site

Yafei Hu and Hung Q. Vu

Abstract: Water main pipes buried in expansive soils are often subjected to severe distress subsequent to installation. Excessive stresses may be induced due to either differential movement of the soils or swelling pressures from the soils along the pipes, impairing their performance or even breaking them. Field monitoring is an important means for understanding soil behaviour and its interaction with water mains. For this purpose, field instrumentation was successfully installed to monitor the performance of a section of water main placed in a well-developed area of a city neighbourhood where more frequent pipe breakage had occurred in recent years. The instrumentation included sensors to measure pipe wall strains, pipe displacement, *in situ* soil water content, soil pressure and temperature. The instruments were installed in both the soil backfill and native soil around the backfill. This paper presents the analyses of monitoring data collected during the first 3 years after instrument installation. It was observed that the soil and pipe behaviour was affected significantly by soil properties and seasonal changes and correlated closely with the change pattern of the local meteorological conditions.

Key words: Soil movement, pipe deformation, climate effect, field instrumentation, expansive soil.

1. Introduction

The behaviour of expansive soils has long been recognized as one of the important factors affecting the performance of buried water mains. Baracos *et al.* (1955) analyzed pipe breakage data for cast iron (CI) water mains in the city of Winnipeg (Manitoba, Canada) for the years 1948-1953 and found that the monthly number of circumferential failures had a cyclic pattern, with two peaks that usually occurred in September and January. The circumferential breakage pattern was compared with the monthly mean temperatures, precipitation, and approximate depth of snow cover, and a close correlation with the monthly weather changes was observed. The high plasticity (i.e., high swelling–shrinkage potential) of soils in Winnipeg was used to explain the observed phenomenon.

Three test installations consisting of instrumented CI and asbestos cement (AC) pipes were made to investigate pipe movement. Up to 50 mm of upward displacement was observed during the investigation. More importantly, differential movement of the buried pipe was observed at all 3 test installations. The differential movement amounted to as much as 20 mm and could cause 0.5° of rotation at the tightened joints. Such movement in corrosion-weakened pipe could well cause flexural or joint failure (Baracos *et al.*, 1955; Kassiff and Zeitlen, 1962).

Mordak and Wheeler (1988) analyzed data from four water authorities in the United Kingdom with a large inventory of AC pipes, one with a predominance of clay soil and the other three having sand and gravel soils. It was found that the monthly distribution of pipe failures for the three areas where sand and gravel soils commonly occurred was random throughout the year, whereas in the area with clay soil, most of the failures occurred during dry, summer months. For the analyzed period from 1952 to 1982 for the water authority with clay soils, two peaks in the annual failure rate were observed, and all corresponded to two hot summers with long dry periods. Also, over 60% of the failures occurred during July, August, and September, when the soil moisture deficit was at a maximum. The breakage pattern was attributed to the shrinkage of the clay soils that causes loading on the buried pipes. The high incidence (over 97%) of circumferential failures, and the large proportion of failures on small

diameter mains (over 98% being 75, 100, and 150 mm diameter, with these pipe diameters representing 80% of the network total length), are typical of breakage patterns resulting from external loading that imposes bending stresses on pipes.

In another study conducted by Hudak *et al.* (1998), the pipe breakage of CI and polyvinyl chloride (PVC) pipe was analyzed in an area having soils with a shrinkage–swelling potential ranging from moderate (3%–6% volume change in an unconfined sample of soil as the moisture content increases from air dry to field capacity) to high (6%–9% volume change) and to very high (more than 9% volume change). Long, hot summers and moderately wet spring and fall seasons characterized the climate of the study area. The highest density of breaks occurred in areas with the highest plasticity indices. Breaks were more common in the smaller 150 and 200 mm diameter pipes. Most of the breaks occurred from September to December, and were attributed to water content increase in the soils that had dried during the summer. From January to May, soil moisture fluctuations were moderate, leading to less swelling and shrinkage and, therefore, lower break frequency. In some years, there was a significant number of breaks in June and July. These breaks were attributed to the short periods of rain that moistened dry soil during these months. The effect on the frequency of pipe ruptures due to soil shrinkage during dry months was also observed in this study. In a 19 month period, there were 8 months with an above–average number of breaks. Each of those 8 months had below average rainfall. The association between plasticity index and break frequency observed in this study suggests that expansive soils may play an important role in premature failure of water pipes.

A study on the failure of asbestos cement water mains in Regina, Saskatchewan, Canada, by Hu and Hubble (2007) analyzed the breakage pattern of the water mains for the period from 1980 to 2004. A monthly breakage pattern that was similar to that of Winnipeg was observed for the 25 year period. The rainfall deficit (a surrogate measure for soil moisture level) and the freezing index (a surrogate measure for the severity of a winter season) were calculated and compared with the annual and winter pipe breakage rates, respectively. It was found that most of the annual and winter breakage rate peaks corresponded to peak rainfall deficits and freezing indices. The highest annual breakage rate also corresponded to a year with the

highest rainfall deficit. Similar to Winnipeg, the soil in Regina is a type of clay with high montmorillonite and thereby high swelling–shrinkage potential.

All these studies reveal a close correlation between high breakage rate of pipes and extreme meteorological conditions where expansive soils are predominant. The soils dry during periods of hot, dry weather due to high temperatures and relatively low precipitation and shrink due to the reduction in moisture content. Conversely, cool wet and rainy periods cause these soils to expand. In general, the soil movement is uneven, and bending stresses are induced on the pipes. In some cases, the stresses are believed to be of such magnitude that they could cause the failure of pipes whose integrity may have already been compromised by other factors such as corrosion (Baracos *et al.*, 1955; Mordak and Wheeler, 1988; Hudak *et al.*, 1998). The high break rate during the winter has also been attributed to frost loading (Monie and Clark, 1974) and thermal stresses (Habibian, 1994; Rajani and Zhan, 1996). The decrease in pipe temperatures during the winter season causes an increase in pipe tensile stresses, which consequently leads to a higher water main breakage rate. On the other hand, the expansion of *in situ* soil moisture upon freezing and the attraction of water to the frost front during frost penetration (segregation or ice lens growth potential) can result in downward pressure on, and displacement of, unfrozen soil below the frost front. Consequently, an increase of earth pressures on the unfrozen soil leads to imposition of additional loads on a water main below the frost front and possible damage of the water main.

In spite of the known influence of expansive soils on the performance of water mains, little work has been done to model the interaction and quantify the relationship, which would be very helpful to municipal engineers for the design, construction, maintenance and management of water mains buried in expansive soils. One possible reason may be the complex factors that can influence local soil moisture conditions. Although an extreme climate condition can be readily associated with an increased pipe breakage rate city-wide, the soil moisture condition may be quite different from one specific location to another in a given jurisdiction. Hamilton (1966) identified many other factors that may influence the local soil moisture condition, including surface features such as pavements, trees, grass cover, adjacent structures and summer watering. For example, trees are usually planted between the

sidewalk and the pavement, on a narrow strip of grassed area. These areas usually receive no artificial irrigation because they are on public property and do not pond water during periods of heavy precipitation because they are well graded. As trees mature, they are forced to extend their root systems to greater distances and depths. A mature tree may extract 0.25–0.5 m³ water per day in the summer (Perpich *et al.*, 1965). If there are pipes in the vicinity of the tree roots, the large water uptake may significantly change the local soil water conditions.

To further understand the working environments and the corresponding responses of pipes in expansive soils, field instrumentation was installed to monitor the performance of a section of water main in an expansive soil in an older area of Regina where frequent pipe breakage has been observed in recent years. The instrumentation included sensors to measure pipe wall strains, pipe displacement, soil water content, soil pressure, and temperature in the soil backfill and native soil around the backfill.

This paper presents the details of the instrumentation and the results of the test section of 150 mm diameter PVC pipe during the 3 year monitoring period. The measured data are first analyzed to reflect their variation characteristics with time. The relationships between the variations and the local meteorological conditions are then discussed. Finally, the effect of the change in the local meteorological conditions on soil and pipe behaviour is identified.

2. Field Installation

Site description

The test site was on Emerald Park Road in the Whitmore Park area of south Regina, Saskatchewan. This location was selected because it is in an area with a high number of AC pipe breaks. It is located near a source of power and adjacent to a park where the instrument enclosure could be located on public land and minimize cable length. It is relatively clear of utilities and has a low number of water service connections, minimizing the risk of public inconvenience.

Trench excavation and backfill

The field installation was carried out between 24 and 28 October 2005. A trench was excavated and the existing AC pipe section was removed. The site plan in Figure 1 shows the location of the trench, which was 2.4 m wide and about 8.2 m long. The AC water main was 2.9 m below the ground surface at this location. Installation of the instrumented section of pipe and other sensors was then carried out at different depths (levels) below the ground surface. The trench backfill was completed to the pavement base level, and the first layer of pavement was placed right after the compaction of the final lift. The top layer of asphalt over the trench area was completed 2 days later.

Sand provided by the city of Regina was used as bedding material. Only one lift was used from the bottom of the trench to the springline of the pipe (about 360 mm thickness) because of the difficulty in compacting the sand around the pipe. This layer, including sand directly below the pipe and the two joints, was compacted manually with a shovel. The trench, from the springline up to the pavement base level, was backfilled with mixed concrete (MC). Mixed concrete is a blend of recycled crushed concrete and subbase gravel at a ratio of 2:1 by weight. It is the primary backfill material currently being used for PVC installation and repair. The MC was installed in lifts of 150 mm up to the level of the underside of the pavement according to the Standard Construction Specifications of the city of Regina (City of Regina, 2004). The backfill was compacted with vibrating plate compactors.

Pipes

The pipe removed from the site was a 4 m long section of 150 mm diameter Class 150 AC pipe, originally installed in 1959. The installed instrumented pipe section was a 150 mm C900 PVC water main pipe. PVC pipe was used because it has relatively low stiffness and, therefore, is very responsive to any soil deformation. It is also the primary pipe material currently being used for water pipe section replacements in this area. Therefore, the field installation closely simulated typical conditions for newly installed replacement water pipes.

The new PVC pipe was 4 m long and had an inside diameter of 155 mm and an outside diameter of 175 mm. It was connected to its adjacent AC pipes by plastic joints (Hu and

Lotfian, 2006). The joints consisted of a PVC plastic sleeve, which was fitted over the end of the pipes, and two rubber rings were compressed between the pipes and sleeve. The joints were quite flexible and can accommodate most deformation by the PVC pipe. Table 1 lists some of the dimensional and physical information of the original AC pipe and the instrumented PVC pipe.

Soil conditions

The stratigraphy of the instrumented site consists of highly plastic lacustrine (Regina) clay, from the surface to a depth of about 9.5 m, underlain by glacial till. Two boreholes were drilled at the site before the installation of the instrumented pipe section. The first borehole (BH1) was in the street, about 1.65 m west of the centreline of the pipe. The second (BH2) was in the Park, about 6 m east of the pipe (Figure 1).

Laboratory testing was conducted on selected soil samples, including index tests, soil-water characteristic curves, saturated hydraulic conductivity tests, swelling tests, constant volume consolidation tests, and measurement of soil suction. Measurement of soil suction was conducted using the filter paper method. Figure 2 shows the soil profile, index properties, measured suction, and dry bulk density at the test site. The laboratory results are summarized in Table 2. The soil tests indicated that natural water contents were slightly below plastic limit for the clay and at about plastic limit for the till.

The particle size distribution curves for soil samples from borehole BH1 at a depth of 4.6 m and borehole BH2 at a depth of 11.0 m are shown in Figure 3. Figure 3 shows that soil at the 4.6 m depth comprised about 80% clay size particles, while the clay till at the 11.0 m depth was 55% clay size material.

The Regina clay was overconsolidated with an overconsolidation ratio of about 5. The measured swelling pressure ranged from 500 to 550 kPa. The clay exhibited significant swelling and shrinkage characteristics upon wetting and drying. Large cracks were observed near ground surface in the park (Figure 4). The cracks were up to 10 mm wide and 1 m deep.

The soil-water characteristic curves of the expansive clay at the test site were characterized. Figure 5 shows the relationship between water content and suction obtained from both the pressure plate test and filter paper methods. Two boundary soil-water characteristic curves (i.e., the drying and wetting curves) can cover the range of data points, as shown in Figure 5. The air-entry value of the soil was about 100 kPa.

The bedding and backfill materials used in this excavation were sampled for laboratory testing. The particle size distribution of the bedding sand and the backfill mixed concrete is shown in Figure 3. The saturated hydraulic conductivities of the two materials were not tested. However, they were estimated using Hazen's equation (Hazen, 1892) to be 10^{-3} – 10^{-5} and 10^{-5} – 10^{-7} m/s, respectively. The water content and dry density were tested *in situ* using a nuclear densometer. The tested dry bulk density of mixed concrete varied from 1721 to 1908 kg/m³ (Table 3).

3. Instrumentation System

Field instrumentation program

The instruments included strain gauges, thermocouples, earth pressure cells, displacement transducers, and soil moisture (WCR) probes. Figure 6 shows a typical section layout and the locations of the sensors that were installed. Some thermocouples and soil water content probes were installed at the same levels as those shown in this figure but in sections away from this one. Table 4 presents the details on the sensors installed at the site.

Strain gauges

Three sets of strain gauges were installed. 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 springlines (Figure 6). Each pair consisted of two separate gauges: one gauge was oriented along the longitudinal axis of the pipe, while the other was oriented along the hoop direction (i.e., perpendicular to the first gauge). The three sets of strain gauges were equally spaced along the pipe section (POS 1–3).

Three dummy strain gauges mounted on small rectangular coupons of PVC pipe identical to the installed pipe material were placed in the backfill close to the three sets of strain gauges on the pipe surface. The apparent deformation due only to temperature change was measured by the dummy strain gauges and the measurements were used to correct the deformation measured by the strain gauges on the pipe surface.

Thermocouples

Forty-nine thermocouples were installed during the field work: 12 thermocouples on the exterior pipe surface to measure the temperatures around the strain gauges, three thermocouples adjacent to the dummy strain gauges to measure the temperatures on the coupons, 33 thermocouples in the backfill and the native soil surrounding the trench to get an insight into the temperature profile around the pipe, and one thermocouple outside the instrument enclosure to monitor ambient air temperature.

Pressure cells

Four pressure cells with 350 kPa capacity were installed in the trench backfill about 170 mm above the top of the pipe (Figure 6). The four pressure cells were placed in two groups of two. In each group, one pressure cell was installed with its flat surface horizontal (to measure vertical stress), while the other pressure cell was placed with its flat surface vertical (to measure horizontal stress). They are called horizontal and vertical pressure cells hereafter, respectively. The pressure cells were surrounded by a thin layer of sand to develop uniform contact between the pressure cells and the backfill.

Rod extensometers

Three rod extensometers were installed, with one end of each extensometer being attached to the instrumented pipe section with a custom-built clamp to make sure that the extensometers had the same displacement as the pipe at the clamped position. The other end of each extensometer was installed in a borehole and anchored to the ground about 6.6 m below the ground surface. The boreholes were sealed with bentonite to prevent water flow into the boreholes and, thus, unintended changes in soil moisture conditions (Figure 7).

Moisture probes

A total of 30 WCR probes were placed in the trench backfill and surrounding native soil to measure the moisture distribution profiles. All probes were installed horizontally, except the four installed about 600 mm below the bottom of the trench, which were placed vertically (Figure 6).

Data acquisition system

An automatic data acquisition system was installed for the full-scale field experiment to monitor pipe deformation, water content, earth pressure, pipe displacements, and soil temperatures in real time on a continuous basis. A Campbell Scientific (Logan, Utah) CR1000-55 datalogger and its peripherals were used to collect the data from the sensors. This system scanned the sensors every hour and the recorded data was transferred daily to an office via a cellular communication link. The data-logging equipment was housed in a metal instrumentation box installed east of the trench inside the park.

Recalibration of instruments

Before their installation in the field, all the instruments were checked in the laboratory for proper functioning. Furthermore, the water content probes were recalibrated. Soil samples with different water contents were prepared, and a probe reading was taken for each soil sample. The volumetric water content was determined using the values of the gravimetric water content and dry bulk density of the soil samples. The regression analysis of the output in microseconds and the volumetric water content obtained in the laboratory resulted in a recalibration equation for the probes (Hu *et al.*, 2010).

4. Field monitoring results

The following results are based on the data collected in the 3 year period following installation from 25 October 2005 to 25 October 2008.

Temperature

Figure 8 shows the average temperatures from representative levels of the installation. Soils at the monitored levels all experienced periodic temperature changes, with seasonal changes in air temperature. Above the pipe level (level 4, or 2.91 m depth), the temperature varied more as proximity to the surface increased; at and below the pipe level, temperature changed at a fairly steady rate and did not go below freezing.

The soil temperatures experienced a minimum temperature in the winter season (i.e., from November to March) and a maximum temperature in the summer season (i.e., from April to October). However, soils at different levels reached their peaks at different times, with soils closer to the ground reaching their peak values earlier. The peak temperatures close to ground surface ranged from -30 °C at the end of January or the beginning of February to +30 °C in mid-July. The peak temperatures at pipe level ranged from a minimum of 3 °C in mid-March to a high of 17 °C towards the end of August.

Figure 9 shows the frost penetration depth during the three winter seasons when monitoring occurred. In general, ground frost started in mid-November. As winter advanced, the frost line (0°C isotherm) penetrated deeper and reached its deepest in mid-March. Thawing of the frost layer started at the ground surface in early March and was completed by the end of March. The thawing line had a much steeper curve than that of the frost line. The maximum frost penetration depth recorded was 1.6 m below the pavement surface at the end of February during the 2007-2008 season.

Soil water contents

Figures 10 and 11 show the variations of typical volumetric water contents at various levels in the trench backfill and in the clay surrounding the trench for the 3 year monitoring period. As shown in Figure 10, WCR3-6 measured the water content in the bedding sand, while all other sensors measured water contents in the mixed concrete. Sensors WCR2-3, WCR3-8, WCR7-3, and WCR9-4 (Figure 11) measured water contents in clays at the trench bottom (4.06 m depth), level 3 (2.93 m depth), level 7 (1.07 m depth), and level 9 (0.45 m depth), respectively. The WCR 9-8 sensor was embedded on the pavement side of the soil at level 9,

close to the middle line of the street. The soil on this side was clay fill, a material that was used as backfill in the past and when the water and sewer pipes were constructed in 1959 at this location. By examining the volumetric water content records shown in Figure 10, the following observations are made:

- Variation patterns in volumetric water content at different depths with time were similar. There was generally a significant jump in volumetric water content following snow melt during late March or early April. The trend of water content increase continued due to relatively higher precipitation from April to July. The water content in the soils generally peaked around late July or early August, with soils closer to the ground surface reaching the peaks earlier. After that, the water content in soil decreased continuously until the next spring when snow melt started again.
- The WCR at level 9 experienced a sudden drop in soil water content in late November or early December and then leveled out. This drop is associated with the freezing of the water at that level (Figures 8 and 9). The soil temperature at this level was below zero in late November or early December. After that, the readings from the probe were not valid. The WCR at level 7 recorded similar reading changes but at a later date, with the sudden drop occurring around late January to early February. Around that time, the frost line reached that level.
- Variations in volumetric water content at each depth were different. The largest variations often occurred near the ground surface (level 7 and above), and the magnitudes of the variations generally decreased with an increase in depth.
- There were some cases of sudden and significant increase in water content. These were attributed to infiltration of rainfall or snowmelt, or water from pipe breaks. These incidents included one on 19 November 2005, which caused a sudden increase in water content for sensors at level 3, including WCR3-6. As a result of such incidents, water from rainfall or snow melt entered into the trench via open joints between the new and old pavement and cracks in the old pavement (Hu and Lotfian, 2006), which is typical for pavements on Regina clay. Another increase in water content occurred on 11 August 2008 due to the break of a section of water main pipe adjacent to the installed PVC pipe. Sensors, including WCR7-4, were lost during the subsequent pipe repair.

- The degree of saturation was relatively constant for sand, with a value of around 48%. However, it varied significantly for the mixed concrete, with a typical range from 40% to 65% and reached full saturation during short periods after snow melt and the pipe break events.

Figure 11 show the volumetric water content records in the surrounding clays. The following observations are made:

- Generally, the variations in volumetric water contents at the top two levels (levels 7 and 9) followed patterns similar to the water content variations in the backfill at the same levels, but at a smaller magnitude, due primarily to the low hydraulic conductivity of Regina clay.
- For clays below pipe levels (levels 2 and 3), the variations in water content were seasonal, without an observable transient effect of rainfall or snow melt events. The clay soil at these levels experienced a water content change of up to 5% during this period.
- Although WCR9-8 is embedded in the clay soils under the pavement, it also experienced a sudden jump in water content at the same time as WCR9-4 during the snow melt period, suggesting that pavement cracks may have significant effect on soil water content under the pavement.
- Clay soils at deep depths (Levels 2 and 3) had experienced relatively small variations in the degree of saturation with a typical range of 79–92%. However, the degree of saturation at the top layers, including WCR7-3 and WCR9-4, varied much more, from around 48% at the end of October to full saturation after snow melt. Full saturation also occurred after major rainfall and the pipe break events.

Soil pressures

Figure 12 shows the variation of earth pressures experienced by the four pressure cells during the three monitored years. In general, the response of the vertical earth pressure cells shows two distinct peaks in each 12 month period: one in the winter season and the other in the summer season. The peaks had similar magnitudes of approximately 100–120 kPa, except for the horizontal pressure cell 1, which recorded a much lower peak of 60 kPa in the 2006 summer season. The reason was not clear. Although horizontal soil pressure increased during

each summer season, no peaks were observed during the winter seasons. The summer peaks varied between 40 and 60 kPa. Although the water main break event on 10 August 2008, had an instant effect on the pressures, no long-term effect was observed – the pressure recovered quickly and proceeded to change according to trends observed before the event.

Pipe displacements

The pipe vertical displacements were measured by three displacement transducers as shown in Figure 13. An initial downward movement was observed for all three locations. The downward movement was induced by increased pressure from the backfill during construction. After construction, the pipe recovered gradually. In general, the response of the displacement transducers showed two distinct valleys in each 12 month period: a small one between mid-February and mid-March in the winter season and a large one between mid-September and mid-October in the summer season. There was a 20 mm difference between the location of the pipe immediately following construction, and the highest displacement was recorded in the summer of 2007.

It was also observed that more rigid body movement was recorded during the three monitored years. However, the pipe did experience different displacements at the three positions. The pipe experienced larger displacements in its mid-span location (POS 2) (see Figure 6) in the beginning than those of the two other measured locations (POS 1 and 3). The relative displacements at the three locations changed with time. The displacement at POS 3 showed a general upward trend, while the displacements at the other two locations (POS 1 and 2) fluctuated around the initial zero displacement position. These differences in vertical movement along the pipe result in bending moments and stresses on the pipe.

Circumferential strains

Figure 14 shows the measured circumferential strains at the midpoint of the pipe section (POS 2). The strains at the other two locations (POS 1 and 3) have the same magnitude and similar response and are not presented. All the sensors experienced a sudden increase in tensile strain when monitoring commenced because the pipe was water pressurized on the

fourth day of construction. After pressurization, the circumferential strains changed periodically in the range between 0.04% and 0.22%.

Longitudinal strains

The measured longitudinal strains at the mid-span section (POS 2) of the pipe are shown in Figure 15. The longitudinal strains at the other two locations have a pattern similar to that shown in this figure and are not included here. It is noted that the strain at the top of the pipe has a negative sign, whereas that on the bottom of the pipe has a positive sign, indicating the pipe at this location was bending downwards during the monitoring period. The strain responses from the two springlines plot between the top and the bottom responses, suggesting that the horizontal deformation of the pipe is not as large as the vertical.

The longitudinal strains of more than 0.06% were recorded during the 3 year monitoring period. Also, a sudden increase up to 0.03% was observed after the water main break on 10 August 2008, indicating that the pipe break and subsequent repair had a significant effect on the longitudinal strains. It appeared that the pipe was stretched during the process, which was consistent with the spike in the pipe displacements as observed in Figure 13.

5. Discussion

Climate was one of the primary contributing factors to the annual failure pattern and monthly failure pattern of AC water mains installed in clay soils as observed by Mordak and Wheeler (1988). Temperature and precipitation (including both rainfall and snowfall) are two climate indices that were frequently cited as main factors. Their effect on pipes and their working environments were also quantified in two other indices: rainfall deficit and freezing index (Kleiner and Rajani, 2002). These climatic factors were analyzed here for their relationship with the observed changes in soil conditions and pipe behaviours.

Air temperature and precipitation data were obtained from a nearby Environment Canada meteorological station (Regina International Airport, Regina, Saskatchewan). Historical

temperature data analysis for the Regina area indicates that the mean monthly temperature is below 0°C for 5 months from November to March. Therefore, these 5 months were used to calculate the freezing index. Table 5 shows the variation in air temperature, precipitation, rainfall deficit, and freezing index values during a 25 year period from 1980 to 2004 (Hu and Hubble, 2007).

Soil temperatures

Soil temperatures versus air temperatures

Figure 8 shows air temperatures and associated soil temperatures at typical levels. The air temperatures varied from as low as -32 °C in winter to as high as +34 °C in summer, with significant daily fluctuations. The annual averages were 7.0, 5.8, and 3.8 °C for the 3 years of monitoring. These values were higher than the averages from 1980 to 2004. As can be seen from Figure 8, the general periodic pattern of variation in soil temperatures closely followed that of the air temperatures, although the magnitude in daily variations decreased with increase in soil depth. The daily air temperatures varied more frequently and significantly, but the temperatures in the soil changed more slowly and less in magnitude. The trend was more pronounced with increase in soil depth. Also there was a time lag in peak temperatures between the soil temperatures and the air temperatures, i.e., the air temperature reached its peak around mid-July, while the soil at level 2 (4.06 m depth) had not reached its peak until mid-September.

Frost depth versus freezing indices

The freezing indices for the winter seasons from 2005 to 2008 were calculated to be 1140, 1615, and 1752 °C • day for the 2005-2006, 2006-2007, and 2007-2008 winter seasons, respectively. They were much warmer for the 2005-2006 winter season and relatively colder for the 2006-2007 and 2007-2008 winter seasons when compared with the freezing indices from 1980 to 2004. A linear regression analysis of the freezing indices against the maximum frost penetration depths for the three winter seasons (Figure 9) found that the maximum frost penetration depth during a winter season is closely related to the freezing index of the air temperatures in the winter season, with higher freezing indices corresponding to deeper frost penetration.

Soil water contents

Soil water contents versus daily precipitation

Figures 10 and 11 also show the daily precipitation for the 3 year period. The daily precipitation varied from 0 mm for most of days to 39 mm on 17 April 2006, with significant daily fluctuations. The annual averages were 372, 398, and 426 mm for the 3 year period, respectively (quite normal for 2007 but dry for 2006 and wet for 2008 when compared with the average annual precipitation from 1980 to 2004). As can be seen from Figures 10 and 11, daily rainfalls significantly affected the soil water content value in the backfill and the clay soils close to the ground surface. However, the effect of rainfall events on soil water content in the deeper clay soil from the ground surface was not so immediate (due to attenuation as water slowly moved), although the soil water content values experienced seasonal changes as well. This relationship is shown in Figure 16. It shows the volumetric water content records and their comparisons with the daily rainfall from 1 March to 1 August 2006. The following observations are made:

- The volumetric water content near the ground surface (e.g., WCR9-6) was the first to be affected by spring frost thawing and snow melt, which generally started in mid-March. Some delays of about 2 weeks in the variations of volumetric water content were observed at the sand layer (WCR3-6) during the snow melt period. The response from moisture probes in the clay below the bottom of the trench (e.g., WCR2-3) was even slower and had not increased until around the end of April.
- Although heavy rainfall events such as those on 16 April 2006, and 10 June 2006 might have eventually influenced the volumetric water contents at all soil levels, they only resulted in a significant transient effect on volumetric water contents at the top two levels monitored by WCR7-4 and WCR9-6, i.e., up to about 1 m below ground surface. These results indicate that the localized short-duration rainfalls of high intensity had much less effect at the pipe level than the long-duration rainfalls of low intensity.
- The volumetric water content also decreased soon after a rainfall event at the upper two levels monitored by WCR7-4 and WCR9-6.
- During the snow melt period, the recorded volumetric water content of the moisture probes at WCR7-4 and WCR9-6 reached the value of soil porosity. Therefore, the top 1 m

of soil was possibly fully saturated. A transient perched water flow was assumed to have developed in the top 1 m.

Soil water contents versus annual rainfall deficits

Figure 17 shows the measured soil water content values and annual rainfall deficits versus time. The annual rainfall deficits were 258, 227, and 142 mm for each year of monitoring, respectively. The first 2 years were relatively dry, while the third year was relatively wet when compared with the average of the annual rainfall deficit for 1980-2004. Except for the winter season when the precipitation accumulates in the form of snow and a short period of time in early spring when rainfall is more heavily concentrated, this area experienced a rainfall deficit for almost half of the year from late June to early November.

It can be seen from Figure 17 that soil water content values at shallow depths in the clays (e.g., WCR7-3) and in the backfill (e.g., WCR3-6, WCR5-2, WCR7-4, and WCR9-6) closely followed the changes in annual rainfall deficits. The general trend was that the soil water content decreased in the winter seasons even though the rainfall surplus (i.e., negative rainfall deficit) increased during this period. This was due to the frozen ground preventing water from flowing into the soil from surface and the precipitation in the form of snow. The snow melt in the spring caused a significant increase in soil water content, and the soil water content values continued to increase due to relatively high rainfall events in May and June even though the rainfall deficits increased during this period. With further increase in rainfall deficit, the soil water content values peaked in July. The time required for water content to reach its peak value increased with depth from the surface. Although there was a decrease in rainfall deficit towards the end of September, the soil water content values continued to decrease due to the accumulated high rainfall deficit. This high rainfall deficit highly desaturated the soils in top layers and prevented water from flowing deeper. This can explain why some small changes in soil water contents could be observed as rainfall deficits fluctuated in May and June, but there was only minor transient response in the soil water content in the late summer season even though there were still fluctuations in rainfall deficits.

Soil water contents at the lower levels of the clay (e.g., WCR2-3) followed similar trends with those described above, but the time lagged even farther behind. The water content values in the clay reached their lowest value towards the end of March when the rainfall surplus was at its maximum. Then the soil water content values increased gradually and reached their maximum when the rainfall deficit reached its peak. After that, the soil water contents continued to decrease until the next spring snow melt. Again, attenuation of the rate of soil water content increase with depth was observed.

Soil pressures

Soil pressures versus freezing indices

As shown in Figure 18, soil pressure increased during the winter seasons and peaked towards the end of each winter season. A comparison between the measured soil pressure and the frost penetration depth versus time profiles indicates that as the frost penetrated deeper, the vertical soil pressure increased correspondingly. When the frost reached its maximum depth, the soil pressures also peaked. However, there were no obvious changes in measured horizontal soil pressures observed as the frost front advanced. Frost penetration depth and the soil pressure versus time for one season, the 2005-2006 winter season, is shown in Figure 19. It shows that any large increase in frost depth caused a similar increase in vertical soil pressure and clearly demonstrates the effect of frost load on soil pressures.

Soil pressures versus rainfall deficit

Figure 20 shows the annual rainfall deficit and its relationship to average horizontal and vertical soil pressures. It shows that changes in soil pressure are closely correlated with changes in rainfall deficit. Soil pressures started to increase in late April or early May when the rainfall deficit became positive and continued to increase as the rainfall deficit accumulated. The soil pressures reached their peaks when the rainfall deficit was at its maximum value. Then, soil pressures fell with the increase in soil moisture (i.e., decrease in rainfall deficit) in early October.

Polyvinyl Chloride pipe is flexible, and the vertical external loading on the pipe can be taken as the prism soil load (Moser, 1990):

$$W = \gamma h B_c \quad [1]$$

where W is the earth load on flexible pipe, γ is the unit weight of soil backfill above the pipe, h is the height of soil backfill above the pipe, and B_c is the pipe outside diameter. The unit weight of the soil backfill above the pipe can be calculated based on the field measured dry density and water content data. From Eq. [1], the soil weight on the pipe was calculated and is shown in Figure 12. The measured vertical soil pressure fluctuated around the predicted soil pressure. The measured maximum frost load ranged from 93 to 104 kPa, about 1.6–1.8 times the calculated earth load. The measured maximum load in the summer seasons ranged from 63 to 122 kPa, about 1.1–2.1 times the calculated earth load.

It should be noted that the calculated vertical soil pressure is based on the field measured dry density and water content data during construction only. As can be seen from Figures 10 and 11, the water content was changing constantly. Also, the soil dry density may also change with time after construction due to soil consolidation and soil volume changes as a result of the change in soil water content as described in previous sections. Therefore, it is expected that the predicted vertical soil pressure will also change with time, if these factors are accounted for in the calculation.

Pipe displacement

Pipe displacement versus soil pressure

Figure 21 shows pipe displacement and change in vertical and horizontal soil pressures versus time. The pipe displacement in summer seasons was dependent on the external loading exerted on the pipe: when soil pressure increased, pipe moved downward. The high frost load in the winter season affected the pipe movement similarly, but the magnitude was much smaller than that due to soil pressure increase in the summer seasons. As the increase in soil pressure was closely correlated to frost load in the winter seasons (Figures 18 and 19) and to the decrease in soil water content in the summer seasons (Figure 17), it was possible to establish a relationship between pipe displacement and meteorological factors, i.e., pipe settles in the summer seasons as a result of the loss in soil water content, which causes soil to shrink and thereby a decrease in soil friction. A reduction in soil friction will increase the soil loads borne by the pipe (Moser, 1990).

Two factors affect the displacement of the pipe in the winter seasons: (i) frozen soils above the pipe put an extra load on the pipe; (ii) soils below the pipe shrink due to a decrease in soil water content as shown in Figure 11. Thus, the bedding soil support to the pipe is weakened. These two factors jointly contribute to the downward displacement of pipe in the winter seasons.

Pipe deformation

Circumferential strains versus temperature

Figure 14 shows the measured circumferential strains and the temperature at the midpoint of the pipe section (POS 2). The close relationship between the measured temperatures and the circumferential strains indicates that the variation of circumferential strains was mainly due to the seasonal temperature variation. Typically, tensile circumferential strains would be anticipated when a pipe is subjected to water pressure changes. However, continuous decrease in strains during the winter season suggests that temperature also plays a significant role.

Longitudinal strains versus temperature

The measured longitudinal strains and temperatures at the mid-span section (POS 2) of the pipe are shown in Figure 15. It can also be seen from the figure that although some peaks in longitudinal strains can be associated with peaks in temperature, the correlation is not as obvious as it is for circumferential strains.

The pipe longitudinal strains consist of two parts: average longitudinal strains and differential longitudinal strains. The average longitudinal strains are the average of the four longitudinal strain values measured at a location along the pipe section and represent the tension or compression deformation along the longitudinal direction. The differential longitudinal strains are the differences between the measured longitudinal strains at each point (top, bottom, and two springlines) of a location and the corresponding average longitudinal strains of the location, and represent the bending deformation of the pipe. The average and differential longitudinal strains at POS 2 were calculated from the measured longitudinal

strains and are shown in Figures 22 and 23, respectively, along with the pipe temperatures at the position. It appears that average longitudinal strains were primarily due to changes in pipe temperature, while the differential longitudinal strains were not temperature sensitive. The differential longitudinal strains were more or less constant after the initial deformation in the first half year (October 2005 – April 2006), which is consistent with the observed original body movement in Figure 13.

6. Summary and conclusions

A site was instrumented to study the behaviour of expansive soils and their effect on water mains buried in the soils. The instrumented site was in an older neighbourhood in Regina with a high number of pipe breaks per year. The sensors installed included thermocouples for soil temperatures, moisture probes for soil moisture content, pressure cells in the backfill soil to monitor the soil pressure near the pipe, rod extensometers to monitor pipe vertical movement, and strain gauges to monitor strains in the pipe wall. The sensors were connected to an on-site datalogger, and monitoring data were transferred daily to a data storage system via a cellular phone link.

The soils at all depths in the backfill showed a pattern of periodic variation in temperatures, and the magnitude in daily variations lessened as depth increased. At and below the pipe level (2.91 m depth), the fluctuation of soil temperature was minor. The general pattern of variation in soil temperatures closely followed that of the air temperatures, but peak soil temperatures lagged behind peak air temperatures. A time lag of up to 2 months was observed for soils close to the bottom of the trench.

Ground freezing started in mid-November, and the frost line penetrated deeper as winter advanced. It reached the deepest level in mid-March. The maximum frost penetration depth during a winter season is closely related to the freezing index of the air temperatures, with higher freezing index corresponding to deeper frost penetration.

The soil water content values in the backfill and the surrounding native soils at shallow depths showed significant variations in response to different weather events, especially snow melt in late March to early April and rainfall events from May to June. At depths of more than 1 m, the seasonal effects in native clay were less obvious. The depth of seasonal variation was significantly affected by the soil permeability as evidenced by different responses by backfill and native soils. Native soils (i.e., Regina clay) have much lower saturated hydraulic conductivities than backfill. However, the two soils showed similar changes in water contents in the top 1 m layer, reflecting the significant effect of cracks in the native soils.

Vertical earth pressure cells experienced two distinct peaks in each 12 month period: one in the winter season caused by frost load and the other in the summer season caused by soil shrinkage due to rainfall deficit. The frost load was about 1.6–1.8 times the soil overburden load while the peak summer load was about 1.1–2.1 times the soil load. Although horizontal soil pressure increased during each summer season, no peaks were observed during the winter seasons. Although a water main break event had an instant effect on the pressures, no long-term effect was observed, as the pressure recovered quickly and resumed pre-event trends.

Significant pipe displacements were observed, and the displacements at the three positions along the pipe section (middle and two ends) were different. At some points, displacement as high as 20 mm was recorded during the monitored period. However, all displacement transducers experienced two distinct dips in each 12 month period: a small one between mid-February and mid-March in the winter season caused by frost load, and a large one between mid-September and mid-October due to summer drying, water content loss, and soil shrinkage.

Seasonal variations were observed for circumferential strains measured in the PVC pipe section. A seasonal pattern was also observed for the average longitudinal strains, while the differential longitudinal strains were relatively constant. The seasonal variations of both the circumferential and average longitudinal strains were primarily attributed to the seasonal soil temperature changes around the pipe and due to high coefficients of thermal expansion of the

PVC pipe. The constant differential longitudinal strains reflected the uniform soil movement around the monitored pipe location.

7. Acknowledgements

The authors extend their appreciation to Mr. Troy LaFreniere, Mr. John Sarasen, Mr. Greg McGorrian, Mr. Brian Wirth, and other members of the field crew from the Engineering and Works Department at the City of Regina, Mr. Kaveh Lotfian, Mr. Paul Kulpate and Ms. Yixiang Wang of NRC-CSIR, and Clifton Associates staff for their valuable assistance during the installation program.

References

- Baracos, A., Hurst, W.D., and Legget, R.F. 1955. Effects of physical environment on cast iron pipe. *Journal of the American Water Works Association*, **42**:1195-1206.
- City of Regina. 2004. Standard construction specifications. Third Electronic Edition, City of Regina Engineering and Works Department, Regina, SK.
- Campbell Scientific. 2004. Instruction manual: CS616 and CS625 water content reflectometers. Campbell Scientific, Inc., Logan, UT.
- Hamilton, J.J. 1966. Soil moisture depletion calculations for Winnipeg, 1950-1963. Division of Building Research, National Research Council Canada, Ottawa, ON. Technical Paper No. 229.
- Hazen, A. 1892. Some physical properties of sands and gravels, with special reference to their use in filtration. 24th Annual Report, Massachusetts State Board of Health, Boston, Mass. Publication Document No. 34, pp.539-556.
- Habibian, A. 1994. Effects of temperature changes on water main breaks. *Journal of Transportation Engineering*, **120**(2): 312-321

- Hu, Y., and Hubble, D. 2007. Factors contributing to the failure of asbestos cement water mains. *Canadian Journal of Civil Engineering*, **34**: 608-621.
- Hu, Y. and Lotfian, K. 2006. Field Installation of an Instrumented Section of Water Main Pipe on Emerald Park Road, October 24 to 31, 2005. National Research Council Centre for Sustainable Infrastructure Research, Regina, SK. Progress Report to the City of Regina.
- Hu, Y., Vu, H.Q., and Hubble, D. 2010. Evaluation of dielectric based probes for expansive soils: application to Regina clay. *Canadian Geotechnical Journal*, 47(3): 346-358.
- Hudak, P.F., Sadler, B., and Hunter, B.A. 1998. Analyzing underground water-pipe breaks in residual soils. *Water Engineering and Management*, **145**:15-20.
- Kassiff, G., and Zeitlen, J.G. 1962. Behavior of pipes buried in expansive clays. *Journal of the Soil Mechanics and Foundations Division, ASCE*, 88(SM2): 133-148.
- Kleiner, Y., and Rajani, B. 2002. Forecasting variations and trends in water main breaks. *Journal of Infrastructure Systems*, **8**: 122-131.
- Leong, E.C., He, L., and Rahardjo H. 2002. Factors affecting the filter paper method for total and matric suction measurements. *Geotechnical Testing Journal*, **25**(3): 322-333.
- Monie, W.D., and Clark, C.M. 1974. Loads on underground pipe due to frost penetration. *Journal of the American Water Works Association*, **66**(6): 353-358.
- Mordak, J., and Wheeler, J. 1988. Deterioration of asbestos cement water mains, final report to the Department of the Environment. Water Research Center, Wiltshire, UK.
- Moser, A.P., 1990. Buried pipe design. McGraw-Hill, NY.
- Perpich, W.M., Lukas, R.G., and Baker, J.C.N. 1965. Desiccation of soil by trees related to foundation settlement. *Canadian Geotechnical Journal*, **2**(1): 23-39.
- Rajani, B.B., and Zhan, C. 1996. On the estimation of frost loads. *Canadian Geotechnical Journal*, **33**(4): 629-641.

List of Tables

Table 1. Dimensions and properties of AC and PVC pipes

Table 2. Soil properties of Regina clay and glacial till at the instrumented site

Table 3. Water content and density of backfills

Table 4. Summary of installed instruments

Table 5. Ranges of air temperature, precipitation, rainfall deficit, and freezing index in
Regina area from 1980 to 2004

Table 1. Dimensions and properties of AC and PVC pipes

Dimension or property	Original AC pipe	Instrumented PVC pipe
Nominal diameter (mm)	150	150
Outer diameter (mm)	183	175
Inside diameter (mm)	153	155
Length (m)	4.0	4.0
Elastic modulus (GPa)	20-25	2.8-4.0
Ultimate tensile strength (MPa)	25	48
Strain to failure (%)	0.1	10
Poisson's ratio	0.3	0.42
Thermal coefficient ($\times 10^{-6}/^{\circ}\text{C}$)	8.5	79

Table 2. Soil properties of Regina clay and glacial till at the instrumented site

Soil property	Soil type	
	Clay	Till
Specific gravity	2.73	
Dry density (kg/m ³)	1400-1680	1900
Natural water content (%)	23-35	12-20
Void ratio	0.93-0.97	
Liquid limit (%)	64-94	38-44
Plastic limit (%)	23-34	14-20
Plastic index (%)	37-66	23-28
Gravel content (≤ 62 mm; %)	0-0.4	0-3.6
Sand content (≤ 5 mm; %)	0.1-1.3	4.2-31.8
Silt and clay content (≤ 74 μ m; %)	98.7-99.9	66.5-95.8
Saturated hydraulic conductivity (m/s)	1.6×10^{-9} - 2.8×10^{-8}	
Swelling index	0.116-0.125	
Corrected swelling pressure (kPa)	500-550	
Matric suction* (filter paper; kPa)	700-3000	2000

* The filter paper method may not be able to measure matric suction greater than 1000 kPa because at this high suction level, most of moisture movement occurs through vapour transfer rather than capillary flow. Whatman No. 42 filter paper was used together with a calibration curve suggested by Leong *et al.* (2002).

Table 3. Water content and density of backfills

Backfill material	Depth (m)	Volumetric water content (%)	Dry density (kg/m^3)	Relative compaction (% of MDD) ^{1,2}
Mixed concrete ¹	0.10	17.5	1721	89
	0.15	18.3	1823	94
	0.30	19.6	1841	95
	0.61	18.6	1813	94
	0.91	20.0	1840	95
	1.22	20.8	1827	95
	1.52	21.4	1908	99
	1.83	19.6	1824	95
	2.13	20.5	1840	95
	2.44	20.3	1814	94
	2.74	21.4	1791	93
Sand ²	3.05	13.4	1819	97

1. Standard Proctor test results: optimum water content = 25.9%, maximum dry density (MDD) = 1930 kg/m^3 .
2. Standard Proctor test results: optimum water content = 22.4%, maximum dry density = 1874 kg/m^3 .

Table 4. Summary of installed instruments

Property measured	Instrument type (and model) ^a	Number of sensors	Measuring range and unit	Burial level or depth
Pipe deformation (strain)	Strain gauge (SK-06-250TM-350 from Micro-Measurements)	24	0 – 1.5%	Level 4
Temperature	Thermocouples (T type from Veriteq Instruments)	49	-190 to +350 °C	Levels 2-10
Soil pressure	Pressure cell (Model 4810X from Geokon)	4	0 – 350 kPa	170 mm above pipe top
Pipe vertical displacement	Displacement (Custom-built 4450 from Geokon)	3	0 – 300 mm	One end, Level 4; opposite end, 6.6 m below ground surface
Soil water content	Water content reflectometer (CS616 from Campbell Scientific (2004))	30	0% – 100% volumetric water content	Levels 2, 3, 5, 7, 9

^aMicro-Measurements, Vishay Precision Group, Malvern, Pa.; Veriteq Instruments, Inc., Richmond, B.C.; Geokon, Lebanon, N.H.

Table 5. Ranges of air temperature, precipitation, rainfall deficit, and freezing index in Regina area from 1980 to 2004

Measurement	Variation range		
	Average	Minimum	Maximum
Average annual air temperature (°C)	3.0	0.1	4.2
Total precipitation (mm)	396	260	593
Annual rainfall deficit (mm)	172	-16	320
Freezing index (°C • day)	1552	1071	2172

List of figures

Figure 1. Location plan of trench, boreholes (BH), water main, and mature trees

Figure 2. Soil profile, index properties, and dry density at the test site (24 October 2005). LL: liquid limit; PL: plastic limit.

Figure 3. Particle size distribution curves for Regina clay and glacial till soil samples and for the sand and mixed concrete backfill materials

Figure 4. Photograph showing tension cracks on the Park ground surface

Figure 5. Soil-water characteristic curves for Regina clay samples

Figure 6. Schematic of sensor layout in typical section

Figure 7. Schematic of rod extensometer connection and installation

Figure 8. Temperature versus time at different levels in the trench

Figure 9. Variation of frost penetration depth with time for three winters

Figure 10. Volumetric water content (VWC) versus time in the trench backfill

Figure 11. Volumetric water content versus time in surrounding clays

Figure 12. Earth pressures in the trench

Figure 13. Pipe displacements

Figure 14. Circumferential strains at the mid-point of the pipe section

Figure 15. Longitudinal strains at the mid-point of the pipe section

Figure 16. Variations of the volumetric water content and daily precipitation from 1 March to 1 August 2006

Figure 17. Measured VWC values and calculated annual rainfall deficit versus time

Figure 18. Relationship between frost penetration depth versus soil pressure

Figure 19. Frost penetration depth versus soil pressure for the 2005-2006 winter season

Figure 20. Rainfall deficit versus soil pressures

Figure 21. Relationship between soil pressure and pipe displacement

Figure 22. Relationship between average longitudinal strain and temperature

Figure 23. Relationship between differential longitudinal strain and temperature

Hu and Vu – Figure 1

Hu and Vu – Figure 2

Hu and Vu – Figure 3

Hu and Vu – Figure 4

Hu and Vu – Figure 5

Hu and Vu – Figure 6

Hu and Vu – Figure 7

Hu and Vu – Figure 8

Hu and Vu – Figure 9

Hu and Vu – Figure 10

Hu and Vu – Figure 11

Hu and Vu – Figure 12

Hu and Vu – Figure 13

Hu and Vu – Figure 14

Hu and Vu – Figure 15

Hu and Vu – Figure 16

Hu and Vu – Figure 17

Hu and Vu – Figure 18

Hu and Vu – Figure 19

Hu and Vu – Figure 20

Hu and Vu – Figure 21

Hu and Vu – Figure 22

Hu and Vu – Figure 23