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Acquisition of Field Data on the Performance of Buried PVC Pipes

Thermal Performance of Trench Backfills and Mechanical Performance of Buried PVC Water Mains for 1993-96

for

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Executive Summary

This report is the third and final of three reports that discusses the field measurements of temperature, axial, flexural and circumferential strains, earth pressures, thermal conductivity and moisture conditions at the PVC water mains renewal project on 77 Avenue between 73 and 75 Street, in Edmonton, Alberta. These measurements were continuously taken between November 10, 1993 and August 30, 1996. The first report discussed the field data for the first monitoring period of November 10, 1993 to June 30, 1994. The second report discussed the field data for the monitoring period of July 1, 1994 to June 30, 1995. The work for the first two monitoring periods work was carried out under the project titled Trench Backfill Pilot Projects which was co-sponsored by National Research Council of Canada and the City of Edmonton. The work for the third period was carried out under a separate project titled "Acquisition of Field Data on the Performance of Buried PVC Pipes" which was sponsored by the National Research Council of Canada, City of Edmonton and Uni-Bell PVC Pipe Association.

Whereas the high flow rates and warm water temperatures obscured the relative thermal performance of the different backfill material during the 1993-94 winter, the bypass line was either kept empty (1994-95) or full of stagnant water (1995-96) to ensure a stable thermal regime which permits an unambiguous thermal evaluation of the different backfill materials. A comparison of temperatures during mid to late winters of 1994-95 and 1995-96 at points some distance beneath the bypass line showed that the temperatures were highest in bottom ash and lowest in unshrinkable backfill sections. The thermal performance of different backfills was also established by determining the maximum frost depth in the trench. The ranking of the backfills in order of increasing maximum frost depth is: bottom ash, Granulite™, 'sand+Styrofoam™', clay, Thermal Crete, sand, and unshrinkable backfill. The measured thermal conductivities of all the backfill materials during the 1994-95 monitoring period were within the range obtained during the 1993-94 monitoring period. Among the backfill materials tested, Granulite™ and unshrinkable fill had the lowest and highest frozen thermal conductivities, respectively. The Granulite™ had very low moisture content and its average thermal conductivity was considerably lower than that measured by Dilger and Goodrich (1990). Although the thermal conductivity of the frozen bottom ash was about two to three times greater than that of the Granulite™, frost penetration was actually less because of the greater moisture available in the bottom ash.

The vertical earth pressures measured just above the 50mm rigid insulation separating the bypass and renewal portions of the trench have clear distinct features during winter and late fall and differed significantly from those during the summer and early fall. The earth pressures increased in the clay and decreased in the sand and unshrinkable backfills, while the frost penetrated the ground. Thus, the so-called 'frost road' effect was significant for the

clayey soil while the corresponding behaviour for sand and unshrinkable backfills was subdued. This difference in behaviour is attributed to the differences in frost susceptibilities of the trench backfill and surrounding soils (Rajani and Zhan 1995).

The axial strains in the bypass pipes embedded in native clay and clean sand did not exceed 300? ? until after the valve was closed to initiate freezing of the water in the pipes (February 1995) and until after the start of the winter of 1995-96. The axial strains decreased after the strain gauges had registered the maximum strains, but not to the original strain levels that prevailed prior to closing of the water valves. As observed in the first period, the axial strains during the warm months in the bypass pipes embedded in unshrinkable fill reached as high as 15OO? ? during the third period. This strain is considerably higher than what was measured during the second cold period. The observations during the warm season of all three monitoring periods confirm that the unshrinkable fill provides more restraint to axial movement than either native clay or clean sand.

The measurements over all three monitoring periods confirm that the overall flexural strains in the bypass (BP) and renewal (RN) pipes embedded in clean sand (section C) and unshrinkable fill (section D) were minor in comparison to those that developed in the pipes embedded in native clay (section B). High flexural strains are more likely to develop when the pipe bridges over nuggets of native clay because it is difficult to place and compact clay uniformly. Therefore, unshrinkable backfill can be used as an alternative to sand for use as bedding material but there has to assurance that it is not stronger than specified because it may be difficult to hand excavate when required. Its mechanical performance will be similar to or better than sand.

The trends in the hoop strains time histories of the bypass pipes were similar for all three backfill materials but the general pattern is distinctly different from that for the renewal pipes. The strain history signatures at the time of valve closure during the second winter were similar to those observed in the first winter, with hoop strains as high as 2354? ? and 4942 in the first and second monitoring periods, respectively. The operational strategy of leaving the water stagnant in the water mains before the onset of frost did not lead to the development of significant hoop strains in the PVC pipe and these strains were far below those measured during the first two monitoring periods. Thus, higher than originally estimated soil restraint was available when the soil around the pipe was not totally frozen. This behaviour suggests that the water within the soil around the pipe freezes much more rapidly than the water within the pipe because of significant differences in the quantity of water that has to undergo phase change.

Thus, the three different operational strategies for freezing water in the line in this project did not lead to the failure of the PVC pipe.

The data from this study clearly indicates that unshrinkable fill does not effectively protect the water in the PVC mains from freezing. Two backfill materials identified for good thermal protection of buried pipes are Granulite™ and bottom ash. The environmental impacts (chemical interaction) of installing PVC water mains in bottom ash have not yet been established but related issues need to be explored further. Granulite™ has been in use in Calgary for some time now and its reported performance has been acceptable from a thermal perspective. On the other hand, unshrinkable fill mitigates the 'frost load' effects but this loading condition is not a significant issue for the structural design of small diameter pipes.

The performance of PVC pipe tested in this project has been acceptable when subjected to three different unfavourable operational strategies. The flow of water substantially reduces the strains imposed on the pipe and every attempt should be made to avoid stagnant water conditions.

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Introduction

This report is the third and final report that describes and discusses the field measurements of temperature, axial, flexural and circumferential strains, and earth pressures measurements at the PVC water mains renewal project on 77 Avenue between 73 and 75 Street, in Edmonton, Alberta. These measurements were taken during the monitoring period of July 1, 1995 to August 30, 1996. Two previous reports (Rajani et al. 1995a, 1995b) discussed the field data for the monitoring period of November 10, 1993 to June 30, 1995. The first two years of the study were financially sponsored by the Institute for Research in Construction of the National Research Council of Canada and the City of Edmonton. Uni-Bell PVC Pipe Association of Texas joined in the collaborative effort for the third and final year of the project in January 1996.

Details of the project objectives discussed in the previous reports (Rajani et al. 1995a, 1995b) are repeated here for ease of reference. A brief description of the backfill materials is restated however the full details on instrumentation and sensors are not repeated since no changes have been introduced that would significantly alter the measurements.

Scope of present study

The major purpose of this study was to evaluate the thermal performance of the different backfills that are either being used currently or those that may be under consideration in the near future. A convenient street location (Figs. 1 and 2) in the south-west of the city was selected as the test site by the Construction Branch of the Water Engineering Department of the City of Edmonton. The study was extended to monitor the longitudinal and circumferential (hoop) strains at selected points on the PVC water mains (Fig. 3) as well as to monitor the eventual failure modes of the buried PVC pipes.

This report discusses the field data for the monitoring period of July 1, 1994 to August 30, 1996. The main objectives of the study may be summarized as follows:

- Evaluate the thermal performance and cost effectiveness of the different types of backfill material (Table 1): Granulite™, native clay (Edmonton clay), clean sand, unshrinkable fill, 'sand+Styrofoam™', Thermal Crete and bottom ash. The field measurement of temperatures and thermal properties in the trench backfill, water temperatures and flow rates were essential to this evaluation.

- Determine the modes of failure of PVC water mains exposed to freezing ground conditions by monitoring strains in PVC pipes buried in selected backfills.

- Conduct measurements of vertical earth loads in selected backfills and relate the variation of loads to climatic and soil conditions and the type of backfill.

Backfill materials

The seven materials used to backfill the different trenches are indicated in Table 1 and are briefly described below:

Granulite™

Granulite™ is a lightweight aggregate (LWA) with high insulation value. Granulite™ is manufactured in a rotary kiln from clay or shale. Chemicals that generate gas under elevated temperatures are added to the base materials to bloat the clay or shale during the sintering process. Granulite™ is then processed to precise gradation to produce an evenly graded aggregate with grain size in the range of 5 to 25 mm.

The physical properties of lightweight aggregate depend on the specific process used in the rotary kiln and may vary according to manufacturer. Nonetheless, it is possible to establish a range of values for its physical properties. The dry density for lightweight aggregate can vary in the range of 700 kg/m^3 to 1000 kg/m^3 which is typically half that of natural soils. In addition, lightweight aggregate is inert, durable, free draining and has relative high strength to native soils. Lightweight aggregate has a high thermal insulation value and low thermal conductivity in comparison to natural soils. The granular characteristic of the lightweight aggregate gives it an angle of friction that is approximately 5° to 10° higher than for typical sand or gravel backfills.

Native clay (Edmonton clay)

The surficial soils in Edmonton may be classified as silty, sand clay with similar gradation characteristics. Since about 40% to 44% of the soil by weight is finer than the No. 200 sieve size, the soil could be classified either as coarse-grained or as fine-grained soil under the Unified Soil Classification system. However, considering that the soils are plastic it is more appropriate to classify these soils as fine-grained with the CL designation. Estimated dry density for Edmonton clay is the range 1100 to 1500 Mg/m^3 with plastic limit of 16% and liquid limit in the range of 29% to 39%.

Clean sand

The sand used for bedding of the renewal pipe was the same as that used for backfill purposes. No gradation characterization for the sand was established but visually it was very uniform with grain size in 0.5 mm to 1 mm range.

Unshrinkable backfill

Controlled low strength material (CLSM) is an unshrinkable backfill and is known by a variety of names. These include: fillcrete, tru-crete, lean concrete backfill, controlled density fill (CDF), K-Krete (a patented CDF). Unshrinkable fill is a mixture of Portland cement, water, fine and coarse aggregates and may contain an air-entraining admixture. Unshrinkable fill is designed to have very low compressive strength compared to concrete and specifications usually limit the 28 day compressive strength to 0.4 MPa.

Thermal Crete

Thermal Crete is a mixture of Portland cement, water, and bottom ash with no aggregate. Thermal Crete fill is designed to have very low compressive strength compared to that of concrete.

Bottom ash

The bottom ash used for backfill purposes was supplied by a local coal power electrical generating plant. The bulk density prior to placement can vary from 580 kg/m^3 to 670 kg/m^3 and after compaction from 790 kg/m^3 to 1360 kg/m^3. Sieve analysis of bottom ash shows that 85% of bottom ash by weight has a grain size less than 2 mm.

PVC water mains

For the last eighteen years, PVC has been the material of choice for the City of Edmonton for replacement of deteriorated metallic pipes. PVC water pipe is available in typical lengths of 6.13 m (20ft) and it is much lighter and consequently easier to handle and install. While metallic pipes are essentially rigid for the range of diameters (150 mm(6") to 300 mm (12")) typically used for water distribution, PVC pipes are flexible in comparison. A proper design for PVC needs to account for this fact. Consequently, the provision of adequate bedding and lateral soil support is an important consideration for the good performance of PVC pipes. The AWWA guide (AWWA 1990) on the design and installation of PVC pipe is widely used by the water distribution industry for these purposes.

The 200 mm (8") PVC pipe used conforms to AWWA standard C900. Pipe lengths of 6.13 m and 3.05 m were used. The principal characteristics of the 200 mm PVC water mains are summarized in Table 2.

Instrumentation details

The installation of the field instrumentation was carried out by NRC staff. The Construction Branch of the City of Edmonton excavated the old water mains and performed all related construction to complete the renewal and bypass water mains installation. Several weeks prior to construction, strain gauges were mounted by NRC/IRC technical staff on specially prepared sections of the PVC pipe at the Coronation Yard facility in Edmonton. These sections of pipe were subsequently handled manually during installation to avoid damage to the strain gauges.

Instrumentation in the backfill materials

Instrumentation to monitor ground temperatures, soil moisture, earth pressures, and thermal conductivity in the different backfill materials was installed during the construction of the water lines. The details on the placement of thermocouples, thermal conductivity probes, time-domain reflectometry (TDR) probes and earth pressure cells were given in the first report and this information is not repeated here except for their locations in the different backfills. It is sufficient to mention that all sensors are responding well even three years after the installation was completed.

Instrumentation of PVC water mains

Micro-Measurements type EA-30-500B1-350 resistance strain gauges with a range of 0 to 50000 micro-strains (? ?) were installed on the PVC pipes to monitor the deformation of both the renewal and bypass water mains at three of the seven test sections (Edmonton clay (section B), clean sand (section C) and unshrinkable backfill (section D)). A total of 64 strain gauges were mounted at mid-length and quarter-length of each 6.13 m PVC pipe section to monitor hoop (circumferential), axial and flexural strains.

An additional six 'dummy' strain gauges were installed to permit temperature corrections. These dummy gauges were mounted on small rectangular coupons prepared from PVC pipe of identical specifications to the pipe installed. These coupons were then sealed in canisters to isolate them mechanically from the surrounding soil, while being responsive to temperature changes comparable to those experienced by the active gauges. Two dummy gauges were installed per test section, i.e., one near the deep renewal pipe and the other near the shallow bypass pipe.

Data acquisition system

Data acquisition at the site was accomplished by linking three Campbell Scientific CR-10 measurement and control modules. This phase of the work was carried out under a contract to Campbell Scientific Canada Corp. in Edmonton. The data acquisition equipment monitored all thermocouples, strain gauges and earth pressure cells at 4 hour intervals. The soil moisture probes (TDRs) and the thermal conductivity probes were read manually for only the first two periods at approximately 2 week intervals, initially by Campbell Scientific Canada Corp. and subsequently by staff at the City of Edmonton. Telephone communication via modems transmitted the collected data from the site to a computer at the NRC Infrastructure Laboratory in Ottawa. Data were received once a day, hourly and daily and it was also stored in on-site memory modules for back-up purposes.

Operational strategies

This experiment was intended to accommodate the needs of a thermal performance comparison of backfill materials and also to investigate the rupture behaviour of a in-service PVC water line during freezing. The relatively moderate weather conditions combined with the high flow rates and warm water temperatures during the first monitoring period kept the bypass line from freezing as intended, and, although the flow was stopped in late winter of 1993-94, complete freezing was not achieved. In addition, the backfill temperature data obtained were so dominated by heat flow from the shallow bypass line as to seriously obscure the relative effects of the different backfills materials themselves.

In addition, during the first winter, hoop strains did not exceed 2360? ? even when the valves were closed to induce the water to freeze. The most likely reason why higher strains did not develop is that the surrounding frozen soil provided restraint as well as the possibility that not all the water had time to freeze. Alternative operating procedure were suggested (Rajani et al. 1995a) to circumvent these difficulties for the second monitoring period of the field experiment. This alternative meant keeping the bypass line empty until the end of January 1995 and subsequently filling up the pipe with water. This operation also failed to cause leaks or pipe rupture. The bypass line was filled with water during the fall of 1995 (third year of monitoring) and kept stagnant throughout the winter of 1995-96. It was anticipated that the highest possible strains are imposed on the pipe when the soil is not totally frozen. However, as discussed later, the PVC pipe still did not develop significant strains and did not fail. The main operational events during the three monitoring periods are summarized chronologically in Table 3.

Field monitoring programme from November 1993 to August 1996

This report discusses the measurements of temperature, axial, flexural and circumferential strains, earth pressures, thermal conductivity and moisture conditions for all three monitoring periods (November 10, 1993 to August 30, 1996).

Earth pressures

Figure 14 shows the vertical earth pressures measured just above the 50 mm rigid insulation (Figs. 5 to 7) during the three monitoring periods at sections, B,C, and D. Two distinct types of earth pressure responses can be distinguished, depending on whether or not there was frost in the ground.

During the spring of the first monitoring period, the earth pressure in the native clay backfill (section B) dropped dramatically as soon as the frozen ground layer had completed thawing, but the pressure steadily increased and hovered around the 'prism' load values during the summer. A similar response was observed during the second and third monitoring periods though the earth pressure drop was not as fast and spanned about 15 to 20 days.

Throughout the summer and fall of 1994, the earth pressure in the sand (section C) backfill steadily dropped from the 'arch' load level to about 50% of the 'arch' load. The response of the earth pressure in sand during the second and third periods has been fairly consistent with the observation that the vertical pressure drops during winter, reaches a minimum just when the thaw period begins and peaks again when the thaw of the frozen ground is complete. However, the earth pressure in sand always remains below the 'arch' load.

During the 1994 spring thaw of the frozen ground layer, the earth pressure in the unshrinkable backfill (section D) increased steadily until about April 15, 1994 when the earth pressure values steadily rose to improbably high levels suggesting equipment or sensor malfunctions. Later, around November 30, 1994, measured values returned to plausible levels. Unfortunately, this pattern of unrealistic earth pressure responses was observed during the second and third periods of monitoring. It is noted that in all instances the earth pressure cell began indicating extremely high values some time after the frozen ground had thawed completely. No such anomalous responses of earth pressure cells embedded in native clay and sand occurred even though more problems may have been expected with these soils.

Examination of the earth pressure responses during the three consecutive monitoring periods with frost in the ground indicates that the initial increase in earth pressures sets in as much as 50 days after the start of around surface freezing. The earth pressure in native clay (section B) increased in the second and third monitoring periods, just as it did in the first period. It is also to be noted that as soon as the thaw began at the surface of the trench, the earth pressure dropped dramatically, then re-established itself once all the backfill had thawed out. Subsequently, during the first few weeks after the thaw was complete in the native clay backfill, the earth pressures dropped again to levels similar to those of the previous summer. As the frost penetrated the ground, the earth pressure in clean sand backfill (section C) remained at an average value of 20 kPa during the first monitoring period, whilst it decreased steadily during the second and third winters, reaching values as low as 1 kPa. There was an upsurge in earth pressure as soon as thawing began but with earth pressure stabilizing at around the 10-15 kPa. By contrast, the earth pressure in the unshrinkable backfill (section D) during all three monitoring periods of frost penetration remained well below that measured for the other two backfill materials. These variations in earth pressures are summarized
in Table 4.

Thermal performance of backfill materials

Thermal properties

The thermal conductivity of the backfill materials was measured using TDR (Time Domain Reflectometry) probes. These measurements are difficult to interpret because steady state conditions of moisture are difficult to establish in a field experiment. The thermal conductivity measurements of the backfills were obtained only during the first two monitoring periods. The unfrozen thermal conductivity of the backfill materials was found to linearly increase with temperature. The increase ranged from 0.6 to 1.7% per °C which is not particularly significant for engineering purposes. Frost penetration is primarily governed by frozen thermal conductivity whilst the unfrozen thermal conductivity only indirectly influences the thawing of frozen ground. The range of thermal conductivity of the backfill materials are summarized in Table 5.

Trench temperatures

The flow of warm (2.9°C to 7.5°C) water in the bypass during the first monitoring period (1993-94) strongly influenced temperatures in the upper levels of each test section, and masked the differences in thermal material behaviour of the different backfills as discussed in the first report. For the winter of 1994-95 the bypass was emptied in September for the second monitoring period in order to get an undistorted thermal performance evaluation of the different backfill materials. The bypass waterline remained filled with water during the third winter (1995-96). Air and pavement temperatures for the three monitoring periods are shown in Fig. 15.

Figure 16 shows representative temperature variations in the trench backfills between the upper and lower PVC water mains for the three monitoring periods. The temperature variations in the second and third monitoring periods clearly show the differences in behaviour attributable solely to the backfill material, since the disturbing influence of the water flow in the bypass line was absent. The data correspond to thermocouple point #8 which is located at a more or less comparable distance beneath the bypass line in each section (Figs. 4 to 10). A comparison of the temperatures from mid to late winters of 1994-95 and 1995-96 provides a rapid appraisal and indicates the superior performance of bottom ash. However, a clearer comparison can be based on the calculated frost depth because the temperature measurement points in all the trench backfills were not located at exactly the same depths below the surface. Figure 17 shows the depth of the 0°C isotherm (frost depth) interpolated from the five-day average temperature data for each test section during the three monitoring periods. The data corresponding to the thaw periods has not been included in Fig. 17. The thermal performance ranking of the backfills on the basis of increasing maximum frost depth is bottom ash, Granulite™, sand+Styrofoam™, clay, Thermal Crete, sand and unshrinkable backfill. This ranking of backfills is consistent with the predictions made by finite element analysis using measured thermal properties, surface temperatures for 1993-1994 and assuming an empty bypass (Zhan et al. 1995). It is interesting to note (Fig. 16) that the frost penetrates earlier in the Granulite™ than in the bottom ash while the thaw can be more or equally rapid in the Granulite™ than in bottom ash during the warming spell in early spring (Fig. 16). This behaviour may be explained by the relatively high moisture content in the bottom ash compared with that in the Granulite™.

The benefits of 50 mm thick rigid insulation in the 'sand + Styrofoam™'section were not always obvious in the second and third monitoring periods. While the frost penetration in the 'sand + Styrofoam' section (Fig. 17) was comparable to that in the clay section during the second period, the frost penetration was not noticeably reduced in the third monitoring period. The sudden apparent decrease in frost depth in the 'sand + Styrofoam™' section in mid-April reflects the small temperature gradients prevailing below the insulation rather than any changes in physical properties. The thermal performance of the Thermal Crete was not nearly as good as that of the bottom ash only. The maximum frost depth recorded for Thermal Crete was in between that for clay and that for sand. Figure 17 also shows clearly that the unshrinkable fill section had the deepest frost penetration of all the trench backfills during the second and third monitoring periods. The maximum recorded frost depth corresponds to the top of the insulation layer. It should also be recalled that the top 0.3 m of backfill in Granulite™, bottom ash and Thermal Crete sections was filled with sand because insufficient backfill materials were available at the time of pipe installation. Therefore, the performance of full depth Granulite™, bottom ash and Thermal Crete sections would therefore be slightly better in practice than what was observed at these tests.

Mechanical performance of PVC water mains

All the strain gauges continue to function well, even though they have now been buried for nearly three years. The output from the strain gauges, especially that from strain gauges placed longitudinally, was treated in the same manner as described in the first report to arrive at the flexural and axial components of strains. In the following sections, the strains measured during the first, second and third monitoring periods are discussed.

Axial strains

Figures 18 to 20 show the measured axial strain histories for both bypass and renewal PVC pipes embedded in native clay, clean sand and unshrinkable fill, respectively. The following comments can be made regarding these axial strain histories:

As expected, it was once again observed that during the winter months, absolute levels of axial strains in the renewal pipes (RN) were consistently lower than in the bypass pipes (BP) regardless of the type of backfill material.

The axial strains in the renewal pipes fluctuated in an approximately sinusoidal manner from tensile (winter) to compressive (summer) within a range of ±400me. While the axial strains were compressive when the frost was in the ground, the strains drifted towards tension during the summer and fall of 1994,1995 and 1996.

The axial strains in the bypass pipes embedded in native clay and clean sand did not exceed 300me until after the water valve was closed to initiate freezing of the water in the pipes on February 6,1995. After the strain gauges had registered the maximum strains, the values decreased, but not to the original strain levels that prevailed prior to closing of the water valves. As anticipated, the renewal pipes did not produce any significant response to the action of freezing water in the bypass pipes.

The net maximum axial strains in the PVC bypass pipes recorded after closing the valves on February 6, 1995 were 1883me (native clay), 2409me (clean sand) and 1529me (unshrinkable fill) compared with 682me,494me and 247me, respectively, after closure of the valves on March 11, 1994. The maximum axial strains measured during the winter of 1995-96 were substantially below those measured in the two previous winters.

While thawing of the backfill had already begun very shortly after valve closure during the first monitoring period, the valves were closed early in the winter of 1994-95 to ensure that water did indeed freeze in the bypass line before the onset of warmer surface temperatures. Nevertheless, it is difficult to argue that, after valve closure, the axial strains measured at mid-length of the span are consistently higher than those at the quarter-length.

It was observed that the axial strains in the bypass pipes embedded in unshrinkable fill during the warmer months (all three monitoring periods) were considerably higher than those measured during colder periods. Axial strains reached as high as 1500me.

High axial strains corrected for temperature effects can be interpreted to lead to more restraint. Thus, the observations for the warmer seasons confirm that unshrinkable fill provides more restraint to axial movement than either native clay or clean sand.

The axial compressive strains after valve closure did not decrease to the values prevailing prior to closure. This behaviour indicates that the frictional restraint provided by the backfill had an influence on the axial strain behaviour of the water pipes. During the first two monitoring periods when water began to freeze in the bypass, the net change in axial strains (Table 6), before and after closure, was greatest in the clay and sand backfills and least in the unshrinkable backfill. This net change in axial strains is opposite to the behaviour observed during the warmer period of 1994-95. The net change in axial strains during the third monitoring period was observed to be the least when compared to change in axial strains during the first two monitoring periods.

The development of axial strains in the pipe is a consequence of complex interactions between water temperature, frictional restraint and shrinkage and swelling characteristics of the backfill, as explained recently by Rajani et al. (1996) and Kuraoka et al. (1996). The axial strain field measurements for the three monitoring periods unequivocally indicate that the axial strains at the 1/2-span length (centre of 6.13m standard pipe-length) are higher than at the 1/4-span length of the pipe. This variation of axial strains is in accordance with the minimum axial restraint at the spigot end of the bell and spigot joint.

Flexural strains

The development of flexural strains should be minimal if each of the standard lengths of PVC pipes were installed in well-compacted trench bedding and backfill. Since flexural strains reflect bending action, it is not particularly significant whether the strains are positive (tension) or negative (compression). The flexural strain histories of the three test sections for the three monitoring periods are shown in Figs. 21-23. In summary, the following points can be made, keeping in mind that the renewal pipe sections are all embedded in sand while the material surrounding the bypass pipes depends on the particular section:

The measurements over the three monitoring periods confirm that the overall flexural strains in the bypass and renewal pipes embedded in clean sand (section C) and unshrinkable fill (section D) are minor in comparison to those that developed in the pipes embedded in native clay (section B).

The flexural strains in the renewal pipes did not vary significantly and did not exceed 150$\mu\varepsilon$. It is to be noted that all the renewal pipes were buried in clean sand.

Flexural strains at both locations (1/2 and 1/4 span) in the bypass pipe embedded in native clay had a cyclic strain variation of ±350 $\mu\varepsilon$ and showed an apparent correlation with surface temperatures or frost penetration. The increase in flexural stresses is in accordance with frost penetration and the concept of frost loads in trenches. In fact, the flexural strains induced in the embedded during frost penetration suggest a possible method for monitoring frost loads.

The above observations indicate that significant flexural strains should not develop if the pipe bedding material is easy to place and compact. Portions of the PVC pipe can bridge over nuggets of native clay since it is neither easy to place nor easy to compact. Additionally, fine-grain soils are more frost susceptible and consequently, flexural strains are expected to be considerably higher in clay than that for pipes buried in clean sand or unshrinkable fill.

During the three monitoring periods the flexural strains for the bypass pipe buried in native clay decreased after mid-March, when the ground surface temperatures (thawing) increased.

In the same monitoring periods, the variation in the flexural strains for pipes buried in clean sand or unshrinkable fill was insignificant.

Hoop (circumferential) strains

Figures 24 to 29 show the measured hoop strain histories for both bypass and renewal PVC pipes embedded in native clay, clean sand and unshrinkable fill, respectively. The following comments can be made regarding these hoop strain histories:

The trends in the time histories (Figs. 24-26) for hoop strains in the bypass pipes (BP) are similar for all three backfill materials but distinct from the time histories for the renewal pipes (RN). The strain history signatures at the time of valve closure in the first two monitoring periods are similar, and changes Table 7 in hoop strain as high as 2354$\mu\varepsilon$ and 4942$\mu\varepsilon$ were recorded in the first and second monitoring periods, respectively. The net change in peak hoop strain registered in the third monitoring period is considerably smaller (1164$\mu\varepsilon$) than expected and certainly lower than that measured in the first two periods. This difference in response can be only attributed to the degree of restraint offered by the surrounding soil when the soil and stagnant water in the pipe were allowed to freeze simultaneously. Thus, it is quite possible that the water within the soil around the pipe froze faster than the water in the pipe on account of the quantity of water in the pipe and its associated latent heat of fusion.

The time it took to develop maximum tensile strains in the PVC pipes during the second period (1994-95) is another indicator on the insulation effects of the backfill. It took longer for the water to freeze for pipes buried in native clay and sand than in unshrinkable fill. The tensile hoop strains decreased rapidly during the thawing period but changed abruptly to compressive strains after thawing was complete.

The time histories of the hoop strains for the renewal pipes (RN) buried in native clay, clean sand and unshrinkable fill have similar trends. Hoop strains as high as ±510$\mu\varepsilon$ developed during all three monitoring periods in the renewal pipes embedded in all three backfills except for sharp fluctuations (> 1000$\mu\varepsilon$) in the sand backfill during the third monitoring period.

Typically, hoop strains at the crown of the renewal pipes (RN) were either near zero or tended to be tensile throughout the two monitoring periods.

The net change in hoop strains in all pipe sections after water valve closure on February 6, 1995 was at least twice as high as that experienced on March 27, 1994. This response confirms that the water line did not freeze completely in the 1993-94 season, as stated in the last report. The radial restraint provided by the different frozen backfill materials does not differ significantly can be inferred from the net changes in hoop strains before and after water freezing during the 1994-95. This response suggests that the stiffness of the frozen backfill is not strongly dependent on the material type. A careful look at the opening and closure of the water valves in the bypass after the first two monitoring periods suggested that filling up and freezing the water in the bypass after the surrounding ground has frozen may not be as detrimental to the performance of the water pipe as what would happen if the water were to freeze simultaneously with the surrounding soil. However, significant hoop strains did not develop as expected when both soil and water in the pipe were allowed to freeze simultaneously during the third period. The fact that hoop strains measured after closing water valves during the first two monitoring periods were the lowest for pipes buried in the unshrinkable backfill suggests that if offers better radial restraint than either clay or sand.

Though hoop strains as high as 4942$\mu\varepsilon$ were registered in the pipe, and instantaneous values may have been higher, a leak detection survey on June 12, 1995 did not indicate any damage to the pipe. Thus, it is clear that, though water expands by over 9% upon freezing, the expansion is effectively restrained by the surrounding frozen soil that limits the development of extreme hoop strains. Significant strains were not registered even when the water in the bypass and surrounding ground freeze simultaneously suggesting that soil freezes earlier than the water within the pipe and consequently the soil does not offer minimal soil restraint as originally anticipated.

Conclusions and Recommendations

Conclusions

Consistent thermal regimes were established in the different backfills by either keeping the bypass empty (1994-1995) or water in it stagnant. These actions avoided the perturbations in the steady state thermal regime as a consequence of the water flowing within the water mains. Hence, an undistorted ranking of the thermal performance of the different backfills was obtained. A comparison of temperatures during mid to late winters of 1994-95 and 1995-96 at points some distance beneath the bypass line showed that the temperatures were highest in bottom ash and lowest in unshrinkable backfill sections. The thermal performance ranking of the backfills from the warmest to the coldest based on the temperatures near the bottom of the trench is: bottom ash, Granulite™, Thermal Crete, sand+Styrofoam™, unshrinkable backfill (fillcrete), clay and sand. Alternatively, the thermal performance ranking of the backfills on the basis of increasing maximum frost depth is: bottom ash, Granulite™, sand+Styrofoam™, clay, Thermal Crete, sand and unshrinkable backfill. The measured thermal conductivities of all the backfill materials during the 1994-95 period were within the range obtained during the 1993-94 period. Among all of the backfill materials tested, Granulite™ and unshrinkable fill had the lowest and highest frozen thermal conductivities, respectively. The Granulite™ had very low moisture content and its average thermal conductivity values obtained were considerably lower than those measured in the 1990 study (Dilger and Goodrich 1990). Although the thermal conductivity of the frozen bottom ash was about two to three times greater than that of the Granulite™, frost penetration was actually less because of the greater moisture available in the bottom ash.

The vertical earth pressures measured just above the 50mm rigid insulation separating the bypass and renewal portions of the trench have clear distinct features during winter and late fall and differ significantly from those during the summer and early fall. The earth pressures increased in the clay and decreased in the sand and unshrinkable backfills while the frost penetrated the ground. Thus, the so-called 'frost road' effect was significant for clayey soil while the corresponding behaviour for sand and unshrinkable backfills was subdued. This difference in behaviour may be attributed to the differences in frost susceptibilities (Rajani and Zhan 1995) of the trench backfill and surrounding soils. It is also to be noted that as soon as the thaw initiates at the surface of the trench, the earth pressure dropped dramatically before reestablishing itself until all the backfill had thawed out. Finally, the earth pressure in native clay backfill dropped again after all the backfill had thawed.

The axial strains in the bypass pipes embedded in native clay and clean sand did not exceed 300$\mu\varepsilon$ until after the valve was closed to initiate freezing of the water in the pipes in February

1995 and until after the start of the winter of 1995-96. The axial strains decreased after the strain gauges had registered the maximum strains, but not to the original strain levels that prevailed prior to closing of the water valves. As observed in the first period, the axial strains during the warm months in the bypass pipes embedded in unshrinkable fill reached as high as 15OOμε during the third period. This strain is considerably higher than what was measured during the second cold period. The observations for the warm season of all three monitoring periods confirm that the unshrinkable fill provided more restraint to axial movement than either native clay or clean sand.

The measurements over all three monitoring periods confirm that the overall flexural strains in the bypass and renewal pipes embedded in clean sand (section C) and unshrinkable fill (section D) were minor in comparison to those that developed in the pipes embedded in native clay (section B). High flexural strains are more likely to develop when the pipe bridges over nuggets of native clay because it is difficult to place and compact clay uniformly. Therefore, unshrinkable backfill can be alternatively used as bedding material with similar or better performance than sand but care has to be taken so that it is not stronger than specified because it may pose difficulties to hand excavate when required.

The trends in the hoop strains time histories of the bypass pipes (BP) were similar for all three backfill materials but the general pattern is distinctly different from that for the renewal pipes (RN). The strain history signatures at the time of valve closure during the second winter were similar to those observed in the first winter, with hoop strains as high as 2354με and 4942με in the first and second monitoring periods, respectively. The operational strategy of leaving the water stagnant in the water mains before the on set of frost did not lead to the development of significant hoop strains in the PVC pipe and these strains were far below those measured during the first two monitoring periods. Thus, higher soil restraint was available when the soil around it is not totally frozen than originally expected. This behaviour suggests that the soil around the pipe freezes much more rapidly than the water within the pipe because of significant differences in the quantity of water that has to undergo phase change. Thus, the three different operational strategies of freezing water in the line did not lead to the failure of the PVC pipe.

The PVC pipe did not rupture or develop a leak after it experienced three different unfavourable operational strategies. Circumstances in the third monitoring period did not permit a final physical check on the occurrence of a leak but all strain measurements indicated otherwise. A final check for rupture or leak wlil be attempted in the summer of 1997. The water in the pipe froze during all three operational strategies but the hoop (circumferential) and axial strains were not significant enough to exceed the allowable strains corresponding to the tensile strength of PVC used in this project.

Recommendations

The data from this study clearly indicates that unshrinkable fill does not effectively protect the water in the PVC mains from freezing. Two backfill materials identified for good thermal protection of buried pipes are Granulite™ and bottom ash. The environmental impacts (chemical interaction) of installing PVC water mains in bottom ash have not yet been established but related issues need to be explored further. Granulite™ has been in use in Calgary for some time now and its reported performance has been acceptable from a thermal perspective. On the other hand, unshrinkable fill mitigates the 'frost road' effects but this loading condition is not a significant issue for the structural design of small diameter pipes.

The performance of PVC pipe tested in this project has been acceptable when subjected to three different unfavourable operational strategies. The flow of water substantially reduces the strains imposed on the pipe and every attempt should be made to avoid stagnant water conditions.

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Table 1 - Summary of trench backfill material and section identification

Backfill Material Type	Section Identification
Granulite™	A
Native Clay (Edmonton Clay)	B
Clean Sand	C
Unshrinkable Fill (Fillcrete)	D
Sand + Styrofoam™	E
Thermal Crete	F
Bottom Ash	G

Table 2 - Description of PVC pipe used at 77 Ave. in Edmonton, Alberta

Pipe Geometry	
nominal diameter, D_n	200 mm
outside diameter, D	229.95 mm
wall thickness, t	12.78 mm
typical pipe length, L	6.13 m or 20 ft

Mechanical Properties	
elastic modulus, E_p (-30°C)	2550 MPa
elastic modulus, E_p (0°C)	2300 MPa
elastic modulus, E_p (+20°C)	2150 MPa
Poisson's ratio	0.45
coefficient of thermal expansion	79 x 10-6/°C
tensile strength	50 MPa
strain at tensile failure	18250 $\mu\varepsilon$
hydrostatic burst pressure	7 MPa
strain at burst pressure failure	2600 $\mu\varepsilon$

Table 3 - Chronology of main operational events

1st monitoring period (November 10, 1993 to June 30, 1994)	
Nov. 93 to March 10, 94	bypass valves open
March 11, 94	bypass valves closed
May 27, 94	CCTV inspection - no damage

2nd monitoring period (July 1, 1994 to June 30, 1995)	
September 94	bypass drained and valves closed
February 6, 95	bypass filled with water and valves closed
June 12, 95	leak inspection survey - no damage

3rd monitoring period (July 1, 1995 to August 30, 1996)	
October 95	bypass filled with water and valves closed

Table 4 - Summary of earth pressures in native clay during the winters of 1993-94, 1994-95 and 1995-96

	1993-94	1994-95	1995-96
minimum pressure after frost in ground, kPa	28.7	19.8	19.8
maximum pressure after, kPa	35.8	31.5	34.0
% increase in earth pressure	25%	59%	72%
time period during increase, days	18.4	14.7	20
peak pressure when thaw begins, kPa	38.6	23.1	24
minimum pressure after thaw, kPa	30.6	8.9	16
% decrease in earth pressure	-21%	-61%	-33%
time period during decrease, days	13.8	12.0	43
peak pressure after minimum, kPa	40.5	31.1	34
% increase in earth pressure	32%	249%	113%
time period during increase, days	23.0	38.6	45
minimum pressure after thaw complete, kPa	21.6	20.7	25
% decrease in earth pressure	-47%	-33%	-26%
time period during decrease, days	35.0	22.1	22

Note: The arrows in Fig. 14 correspond to time and the earth pressures noted in this table.

Table 5 - Summary of thermal conductivities for various trench backfill materials

Backfill material type	Thermal conductivity at 0°C W/m°K	
	unfrozen	frozen
Granulite™	0.12 - 0.14	0.11 - 0.13
Native clay (Edmonton clay)	1.30 - 1.40	1.60 - 1.80
Clean sand	2.00 - 2.30	2.10 - 2.80
Unshrinkable fill (fillcrete)	2.00 - 2.20	2.90 - 3.20
Thermal Crete	0.87 - 0.89	-
Bottom ash	0.35 - 0.40	0.22 - 0.30

Table 6 - Summary of axial strains after valve closures in winters of 1993-94, 1994-95 and 1995-96.

		1993-94	1994-95	1995-96
Native clay	minimum axial strain before valve closure, με	-112	406	417
	maximum axial strain after, με	-794	-1477	53
	net increase in axial strain	682	1883	364
	time period during increase, days	19	73	17
Clean sand	minimum axial strain before valve closure, με	-77	232	841
	maximum axial strain after, με	-571	-2177	338
	net increase in axial strain	494	2409	503
	time period during increase, days	23	60	17
inshrinkable fill	minimum axial strain before valve closure, με	-124	59	368
	maximum axial strain after, με	-371	-1471	-294
	net increase in axial strain	247	1529	662
	time period during increase, days	31	59	18

Note : The arrows in Figs. 18-20 correspond to time and the axial strains noted in this table.

Table 7 - Summary of hoop strains after valve closures in winters of 1993-94, 1994-95 and 1995-96.

		1993-94	1994-95	1995-96
Native clay	minimum hoop strain before valve closure, με	-677	-1077	-1252
	maximum hoop strain after, με	1677	3865	-88
	net increase in hoop strain	2354	4942	1164
	% increase with respect to unshrinkable fill	49%	7%	-513%
	time period during increase, days	16	67	17
Clean sand	minimum hoop strain before valve closure, με	7	-529	-412
	maximum hoop strain after, με	2052	4235	-59
	net increase in hoop strain	2045	4764	353
	% increase with respect to unshrinkable fill	30%	3%	-225%
	time period during increase, days	13	65	10
Inshrinkable fill	minimum hoop strain before valve closure, με	-269	-592	-270
	maximum hoop strain after, με	1304	4035	-552
	net increase in hoop strain	1574	4627	-282
	time period during increase, days	16	48	13

Note: The arrows in Figs. 24-29 correspond to time and the hoop strains noted in this table.

Figure 1 - Site location for trench backfill study in Edmonton, Alberta

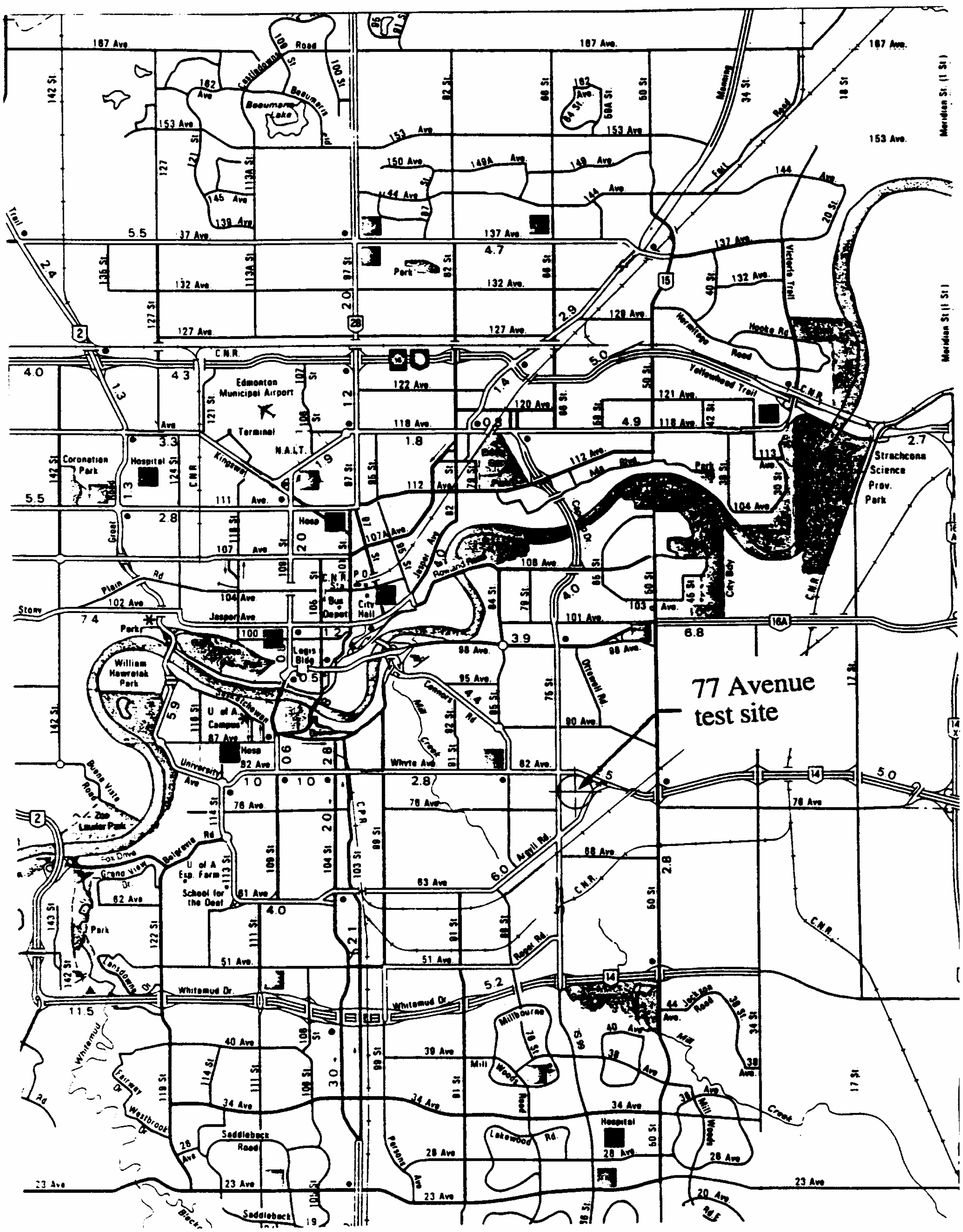

Figure 2 - Site Plan at 77 Avenue between 73rd and 75th streets, Edmonton, Alberta

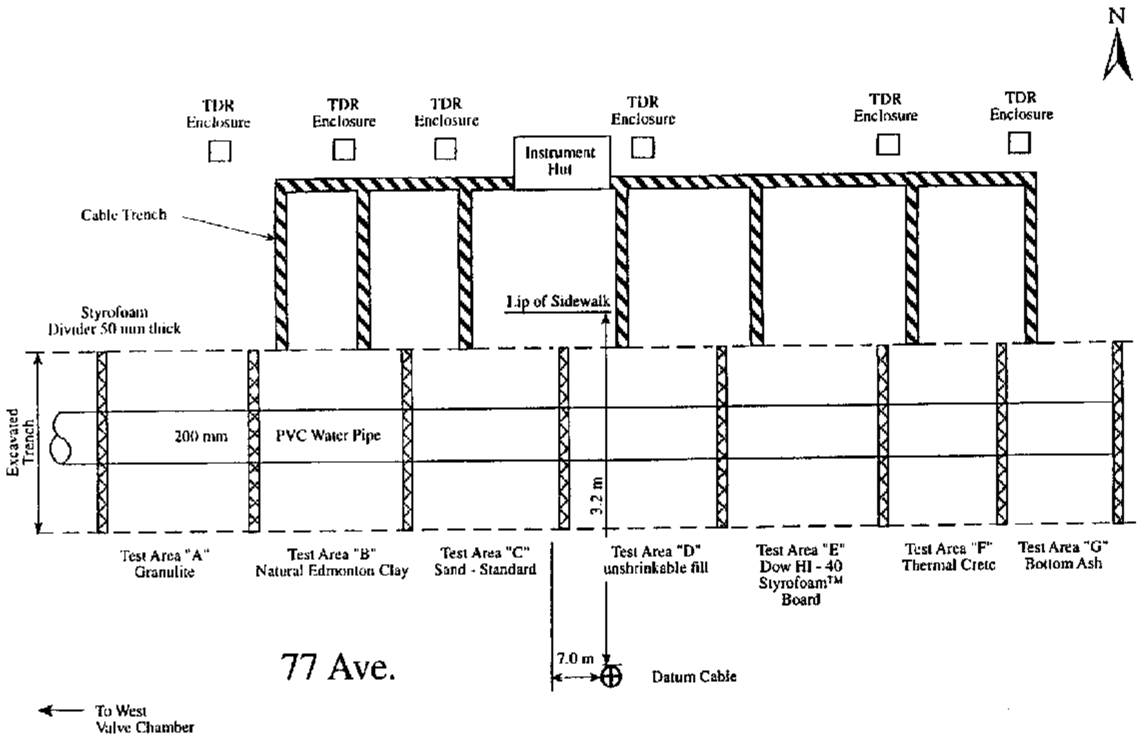

Figure 3 - Typical cross section showing locations of bypass and renewal water mains

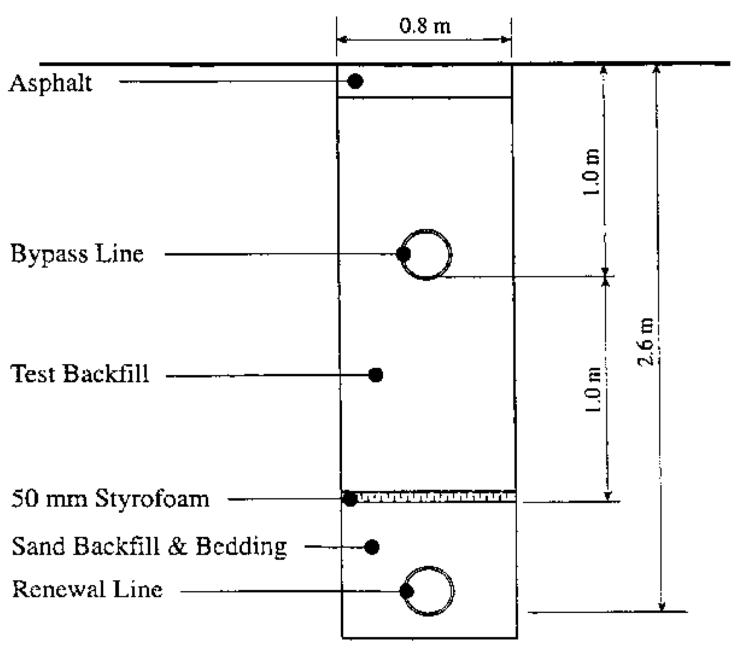

Figure 4 - Backfill materials and sensor locations for test section A with Granulite™

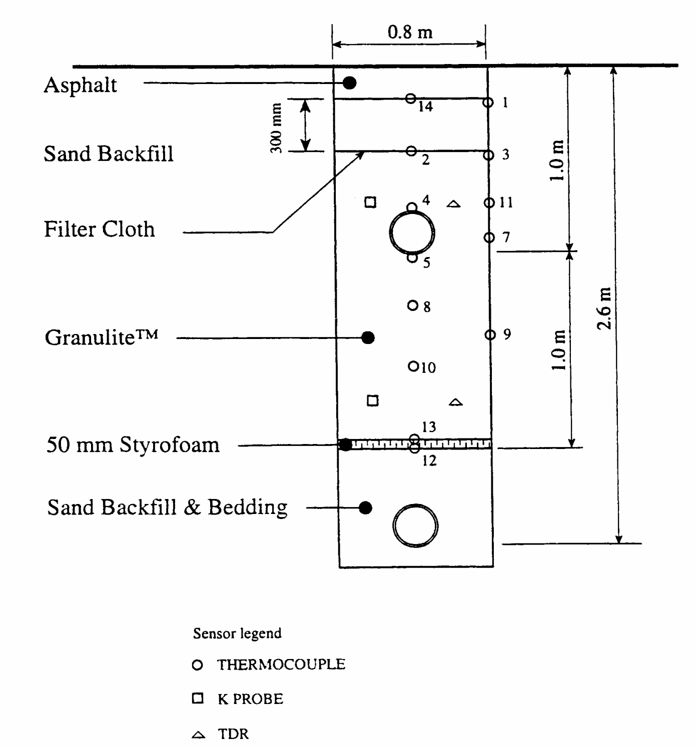

Figure 5 - Backfill materials and sensor locations for test section B with native Edmonton clay

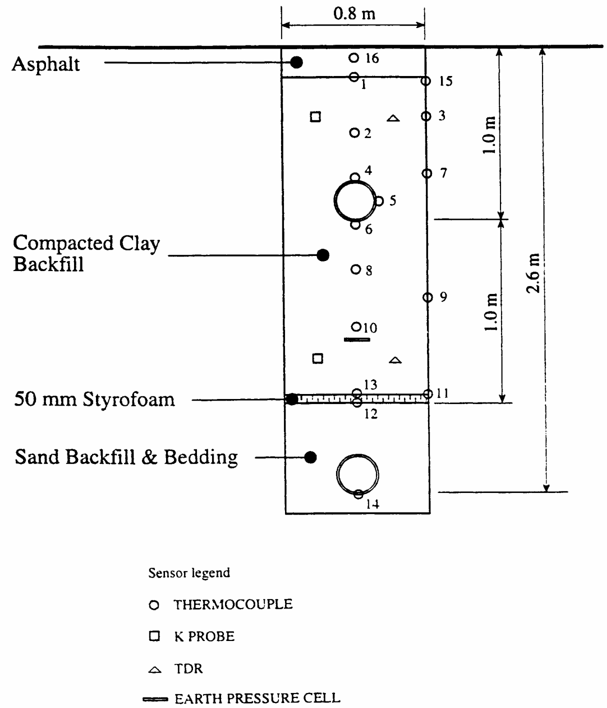

Figure 6 - Backfill materials and sensor locations for test section C with clean sand

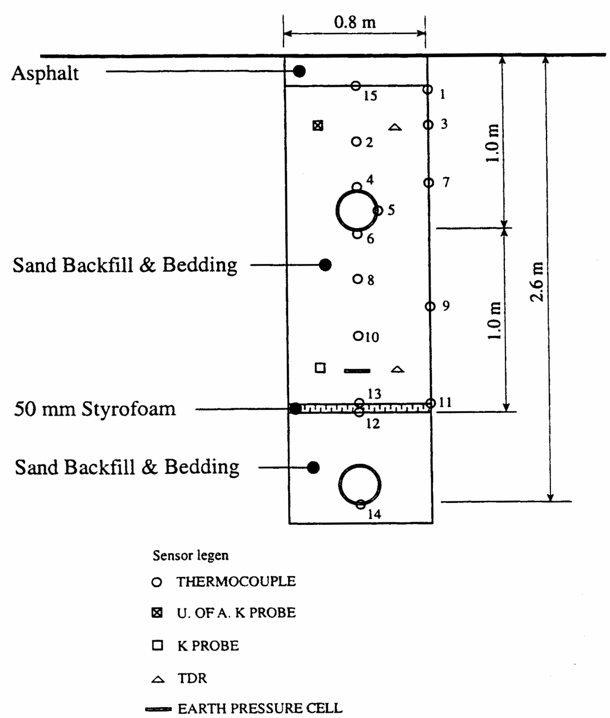

Figure 7 - Backfill materials and sensor locations for test section D with unshrinkable fill

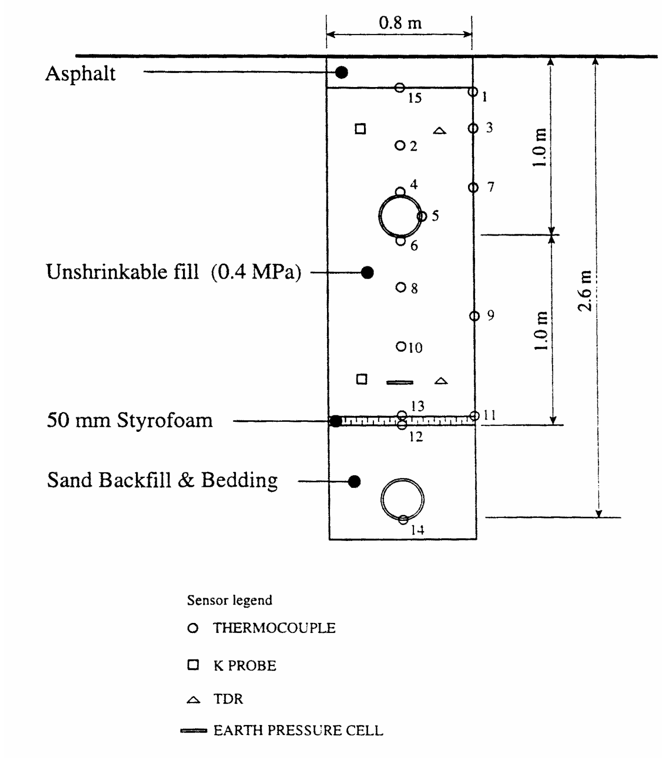

Figure 8 - Backfill materials and sensor locations for test section E with sand and Styrofoam board

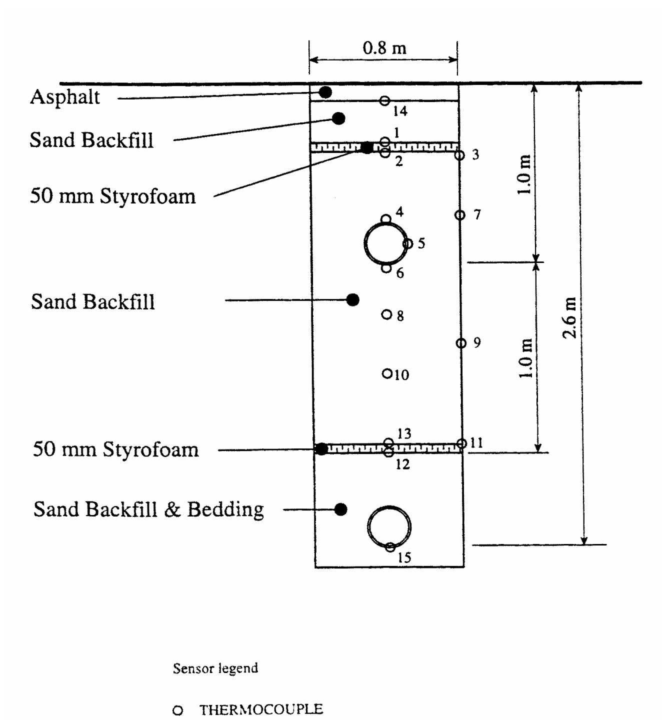

Figure 9 - Backfill materials and sensor locations for test section F with Thermal Crete

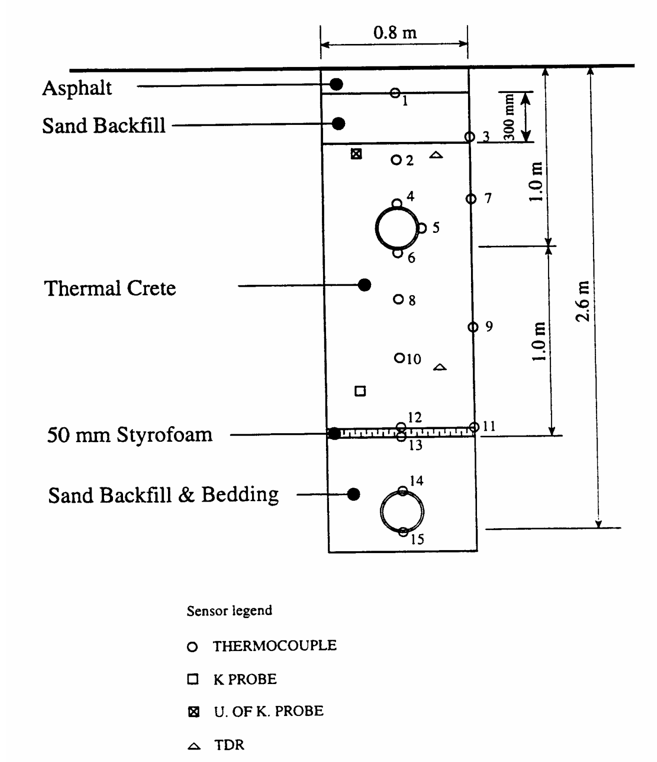

Figure 10 - Backfill materials and sensor locations for test section G with bottom ash

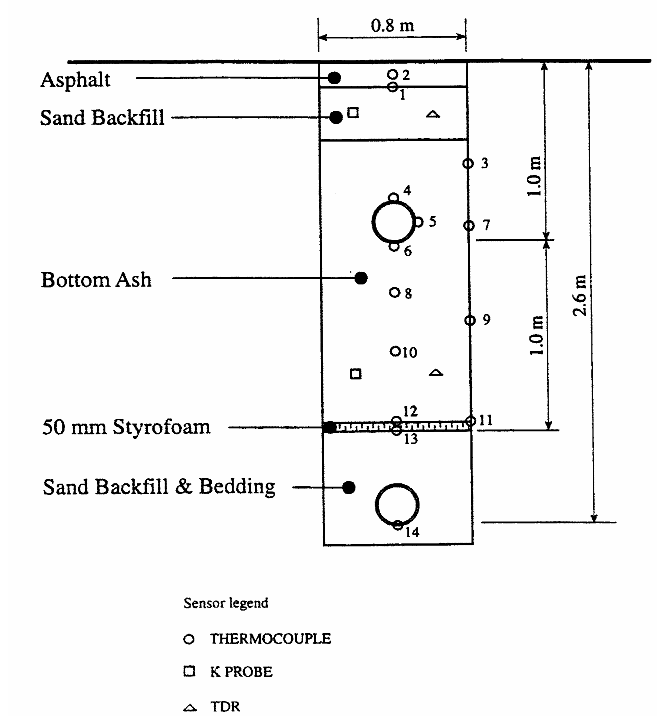

Figure 11 - Longitudinal section of bypass and renewal pipes with native clay trench backfill (section B)

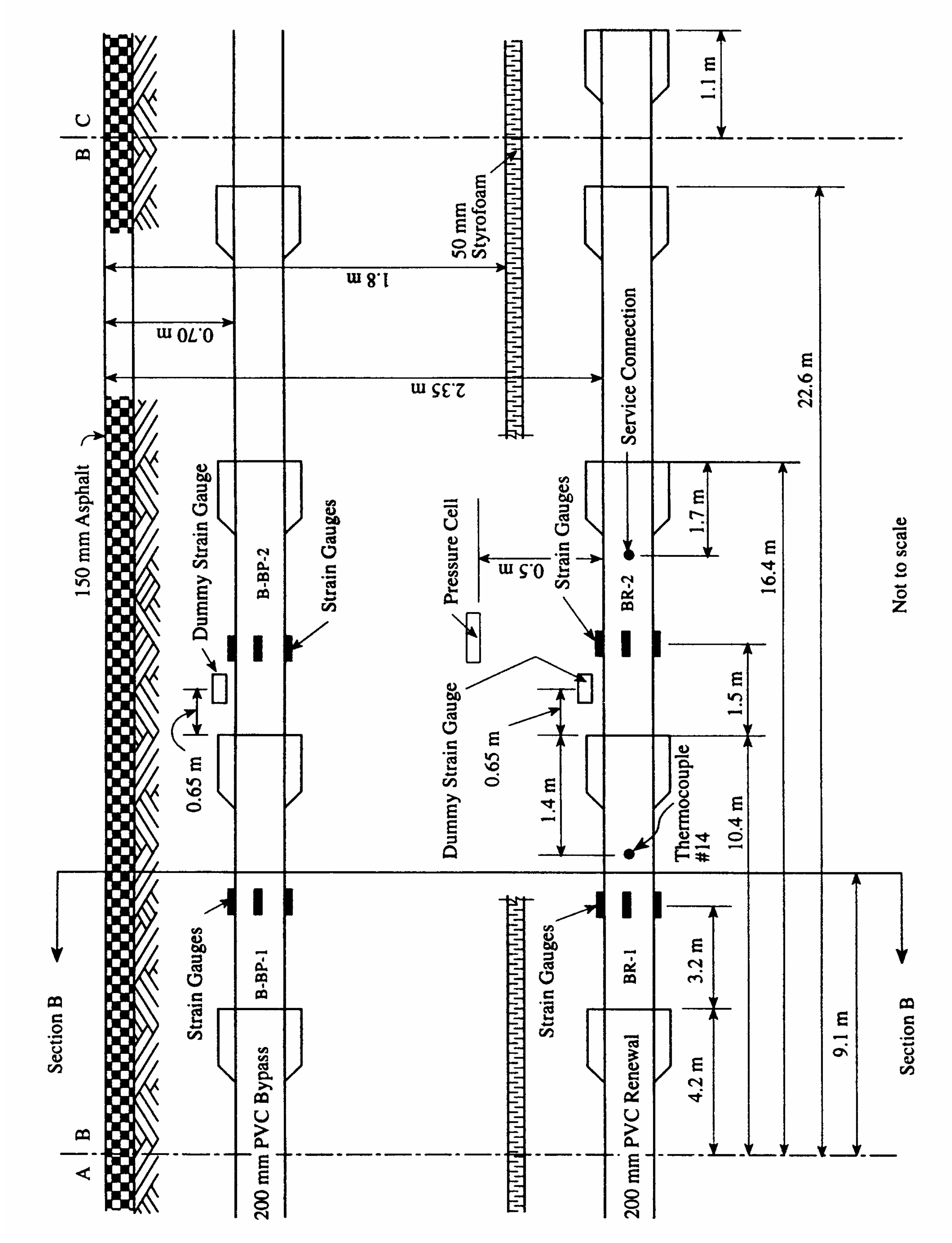

Figure 12 - Longitudinal section of bypass and renewal pipes with clean sand trench backfill (section C)

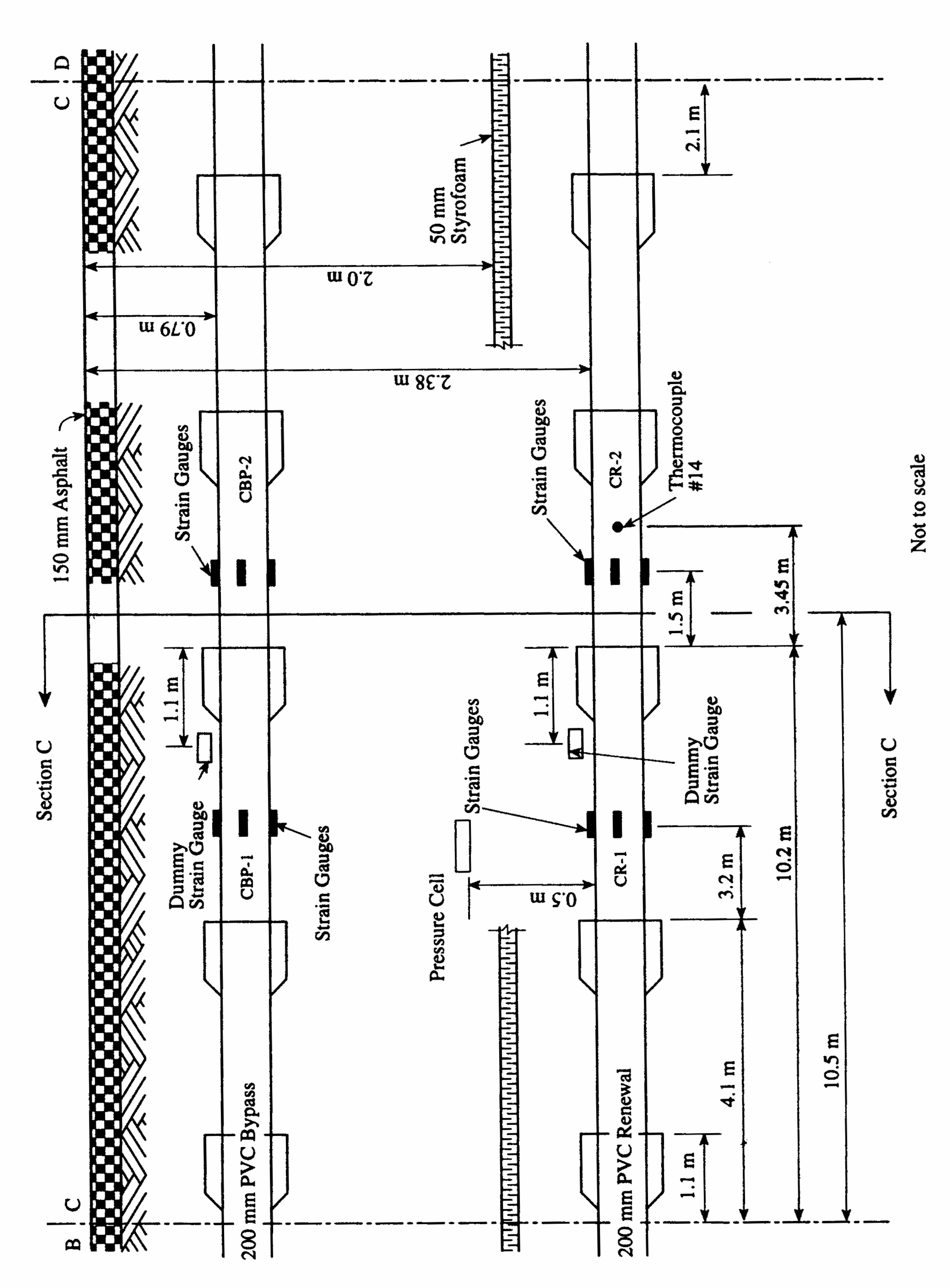

Figure 13 - Longitudinal section of bypass and renewal pipes with Fillcrete trench backfill (section D)

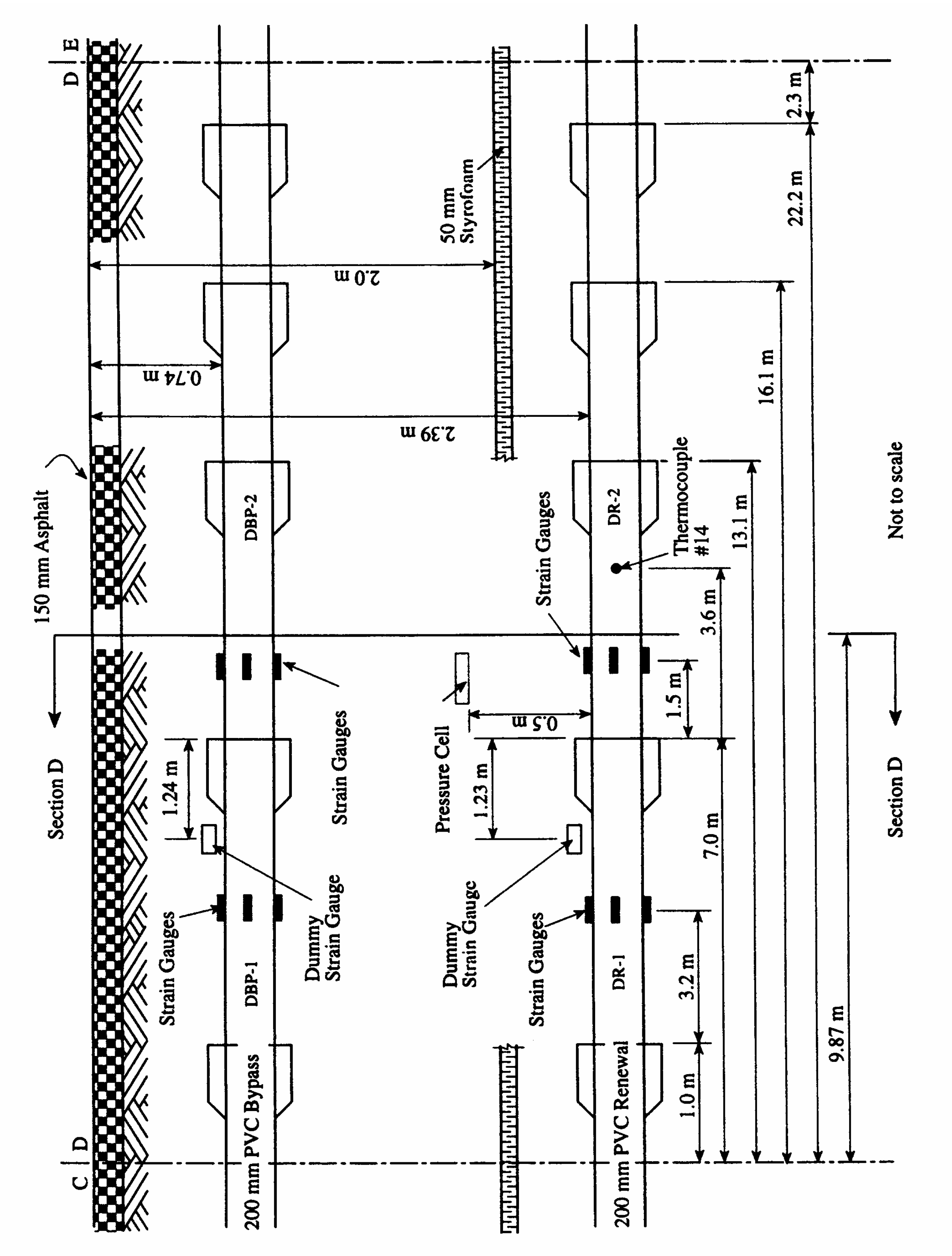

Figure 14 - Histories of vertical earth pressure and frost depths in native clay, clean sand and unshrinkable backfill : 1993-1996

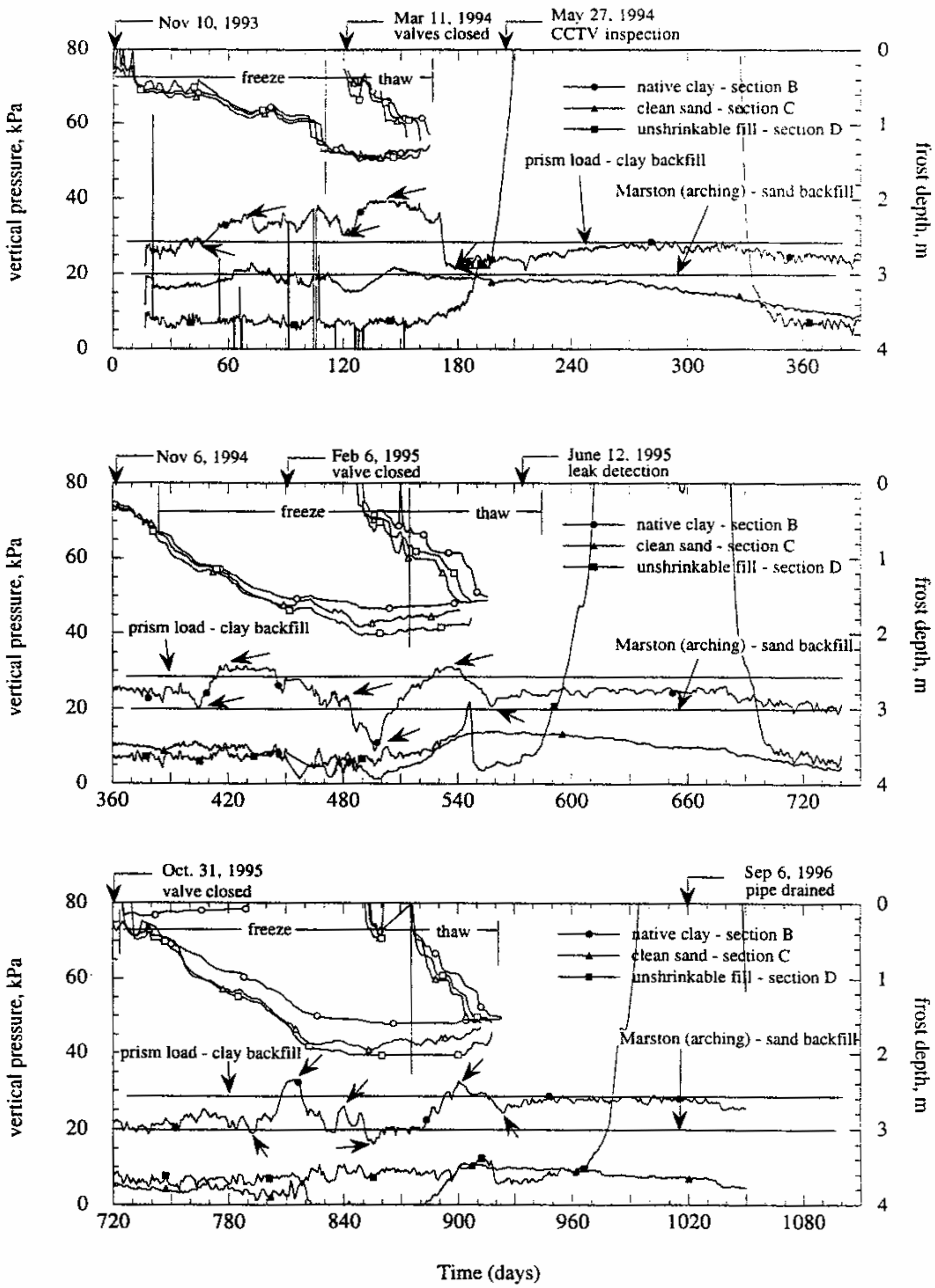

Figure 15 - Variation of air and surface temperature with time during 1993-1996

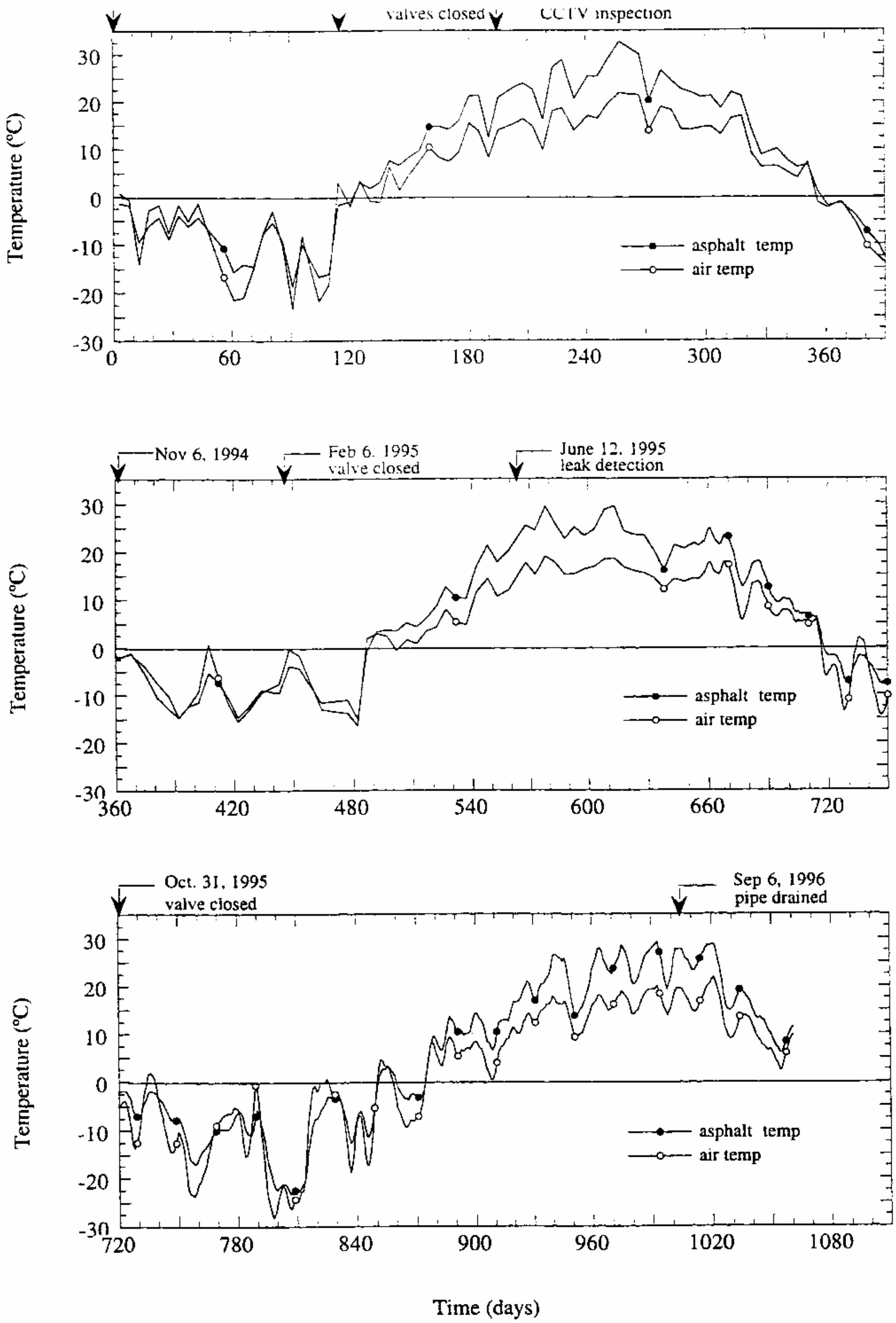

Figure 16 - Variation of temperature with time at thermocouple No. 8
for all seven sections during 1993-1996

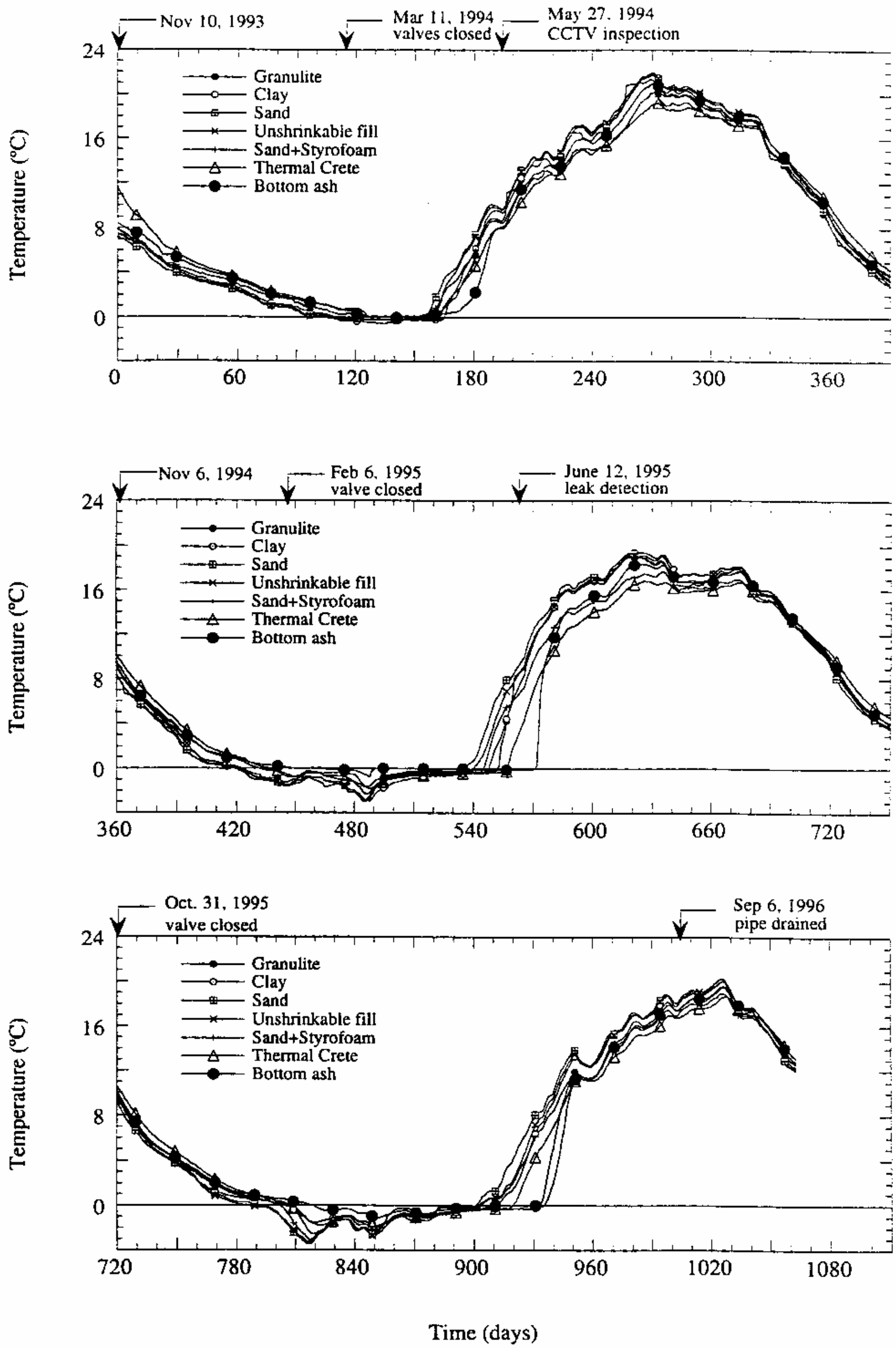

Figure 17 - Variation of frost depth with time at centreline of trench for all seven sections during 1994-1996

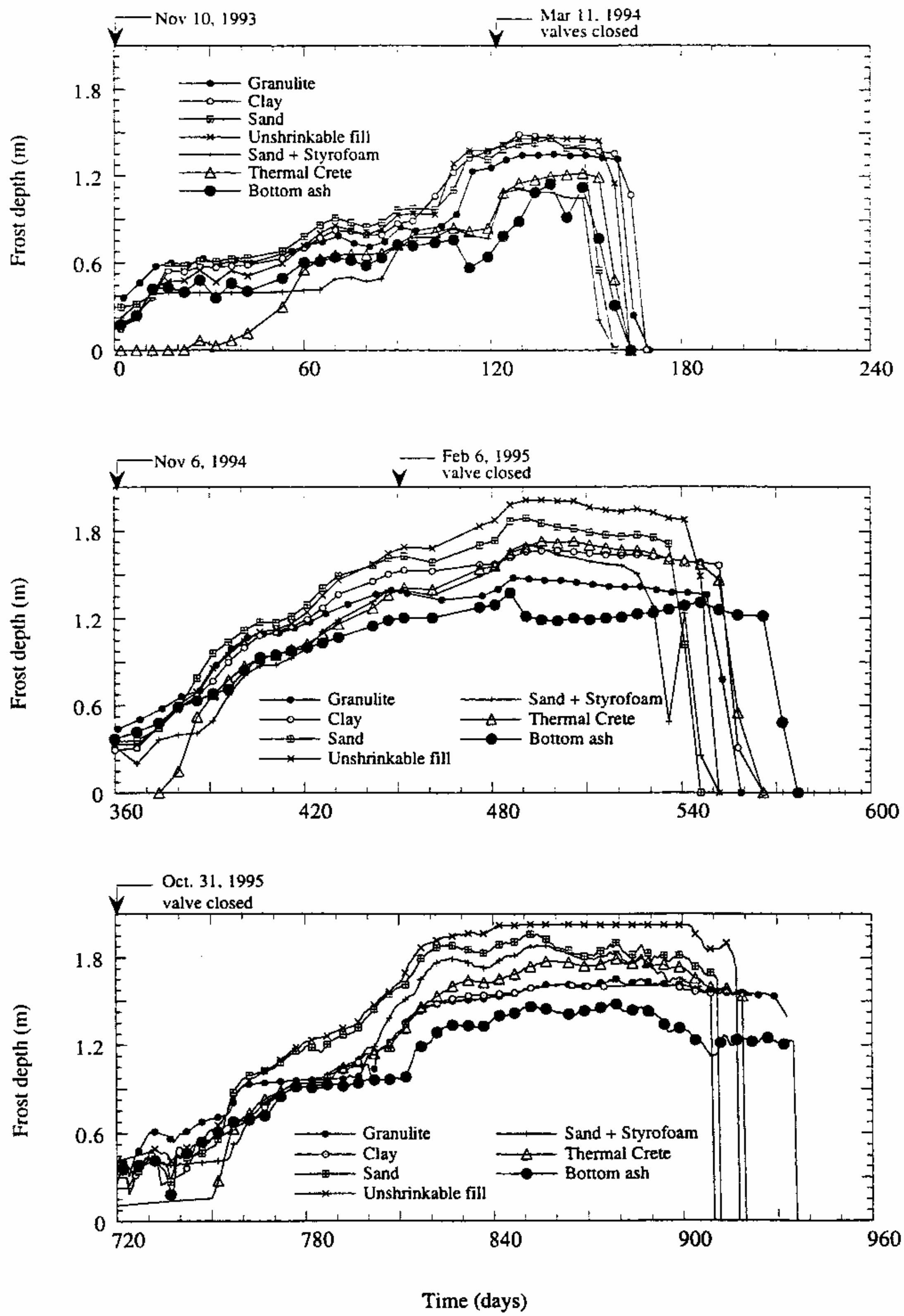

Figure 18 - Axial strain histories of bypass (BP) and renewal (RN) PVC pipes buried in native clay (section B) : 1993-1996

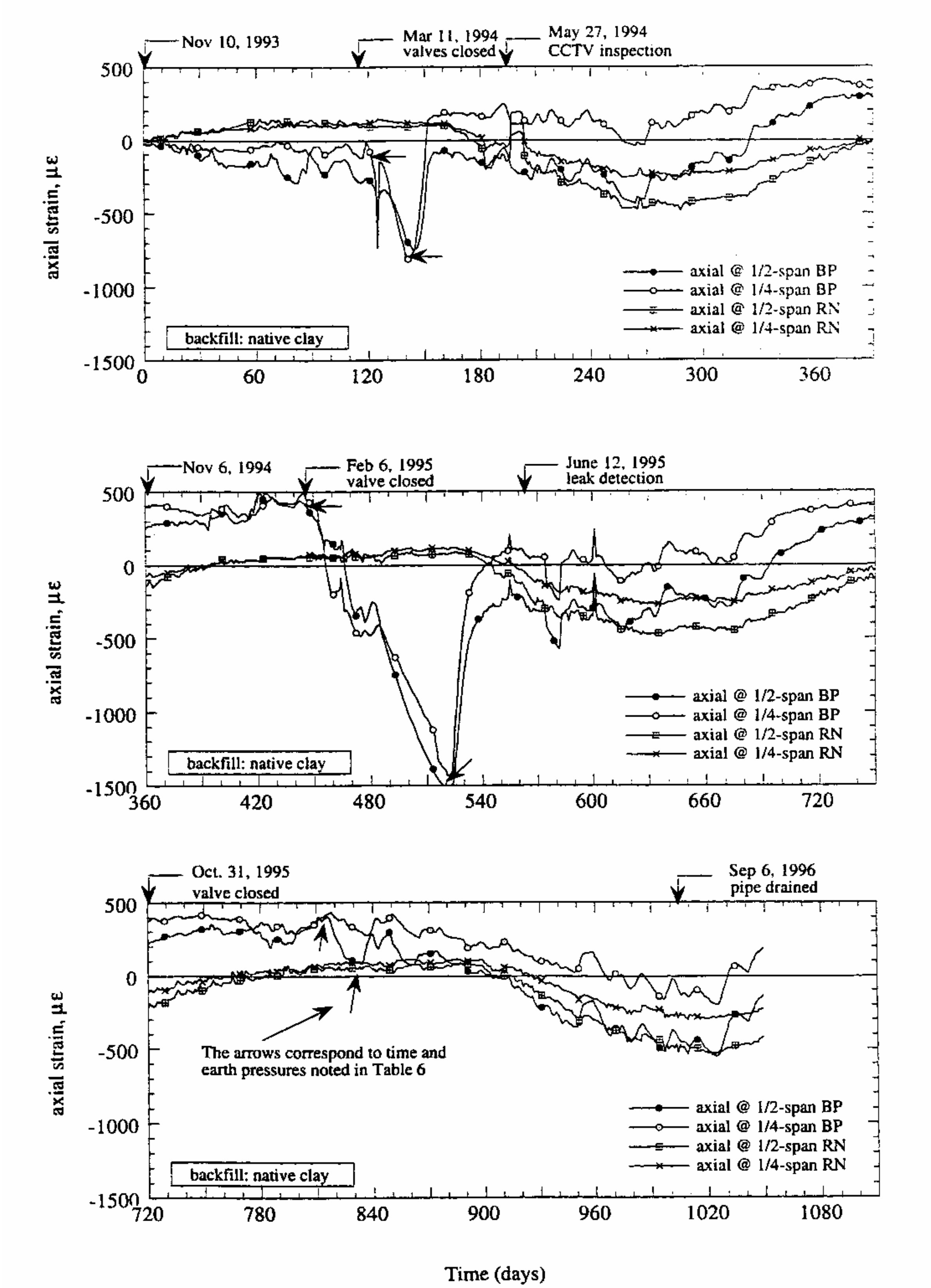

Figure 19 - Axial strain histories of bypass (BP) and renewal (RN) PVC pipes buried in clean sand (section C) : 1994-1996

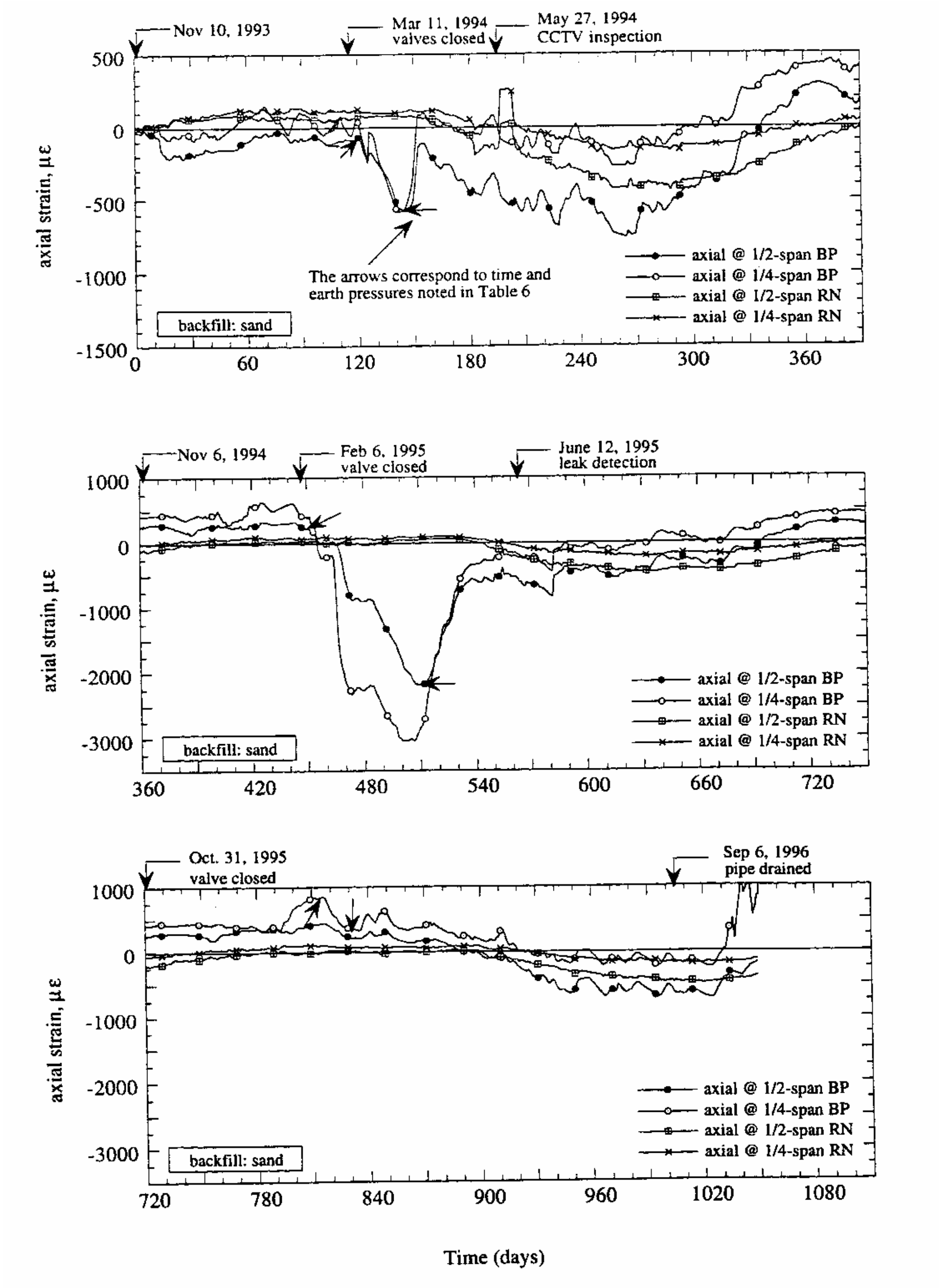

Figure 20 - Axial strain histories of bypass (BP) and renewal (RN) PVC pipes in unshrinkable fill (section D) : 1993-1996

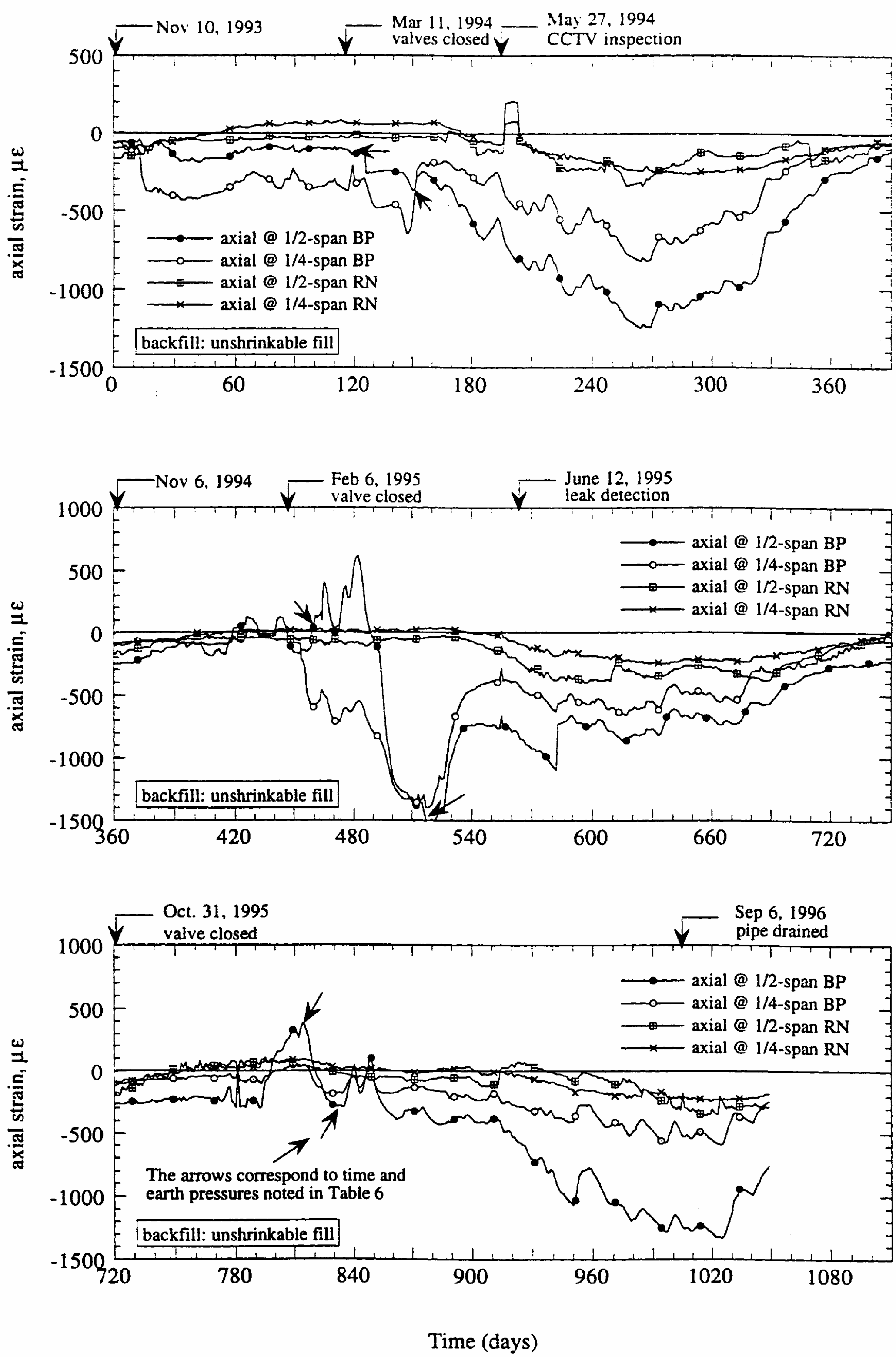

Figure 21 - Flexural strain histories of bypass (BP) and renewal (RN) PVC pipes buried in native clay (section B) : 1993-1996

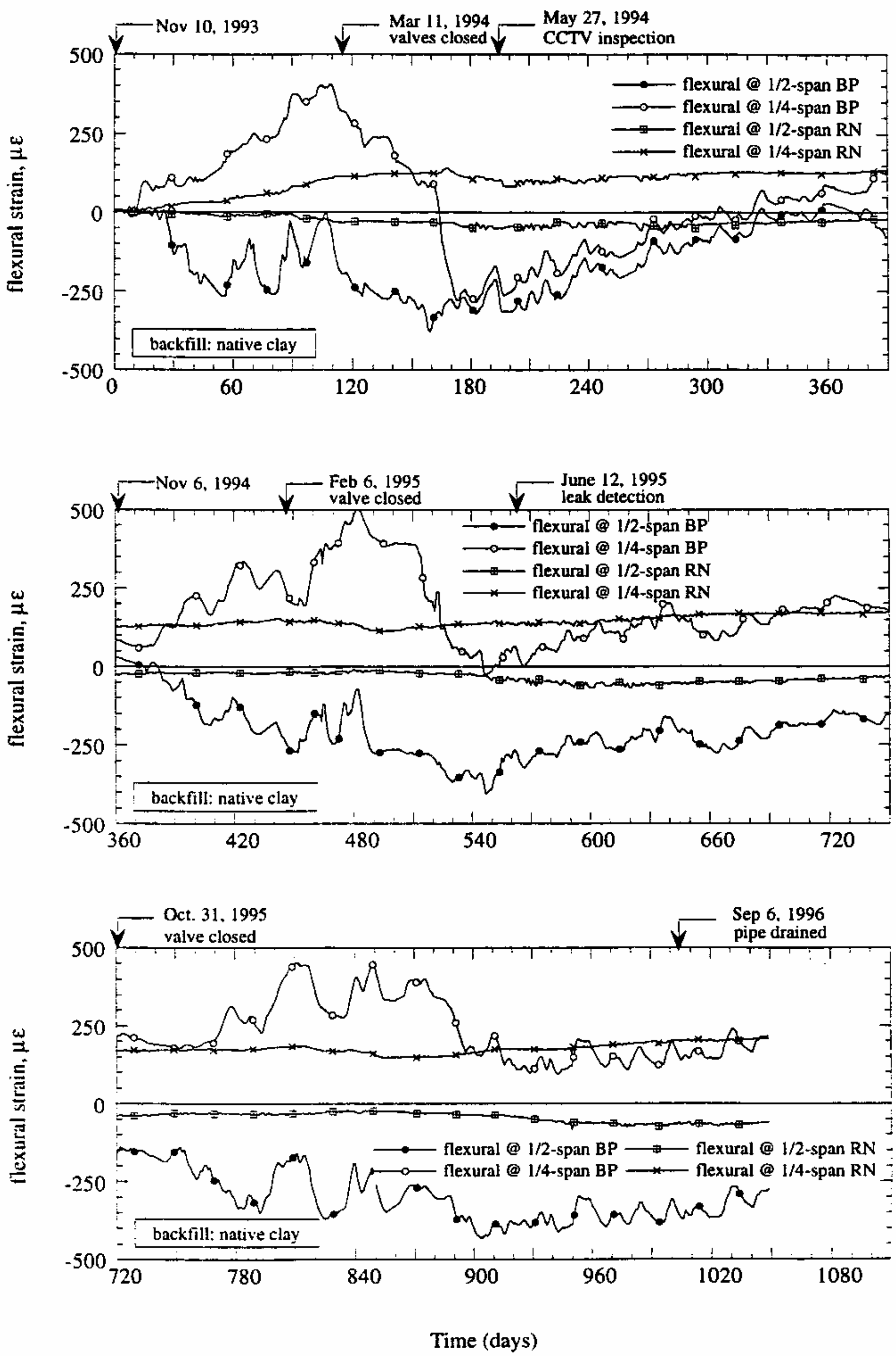

Figure 22 - Flexural strain histories of bypass (BP) and renewal (RN) PVC pipes buried in clean sand (section C) : 1993-1996

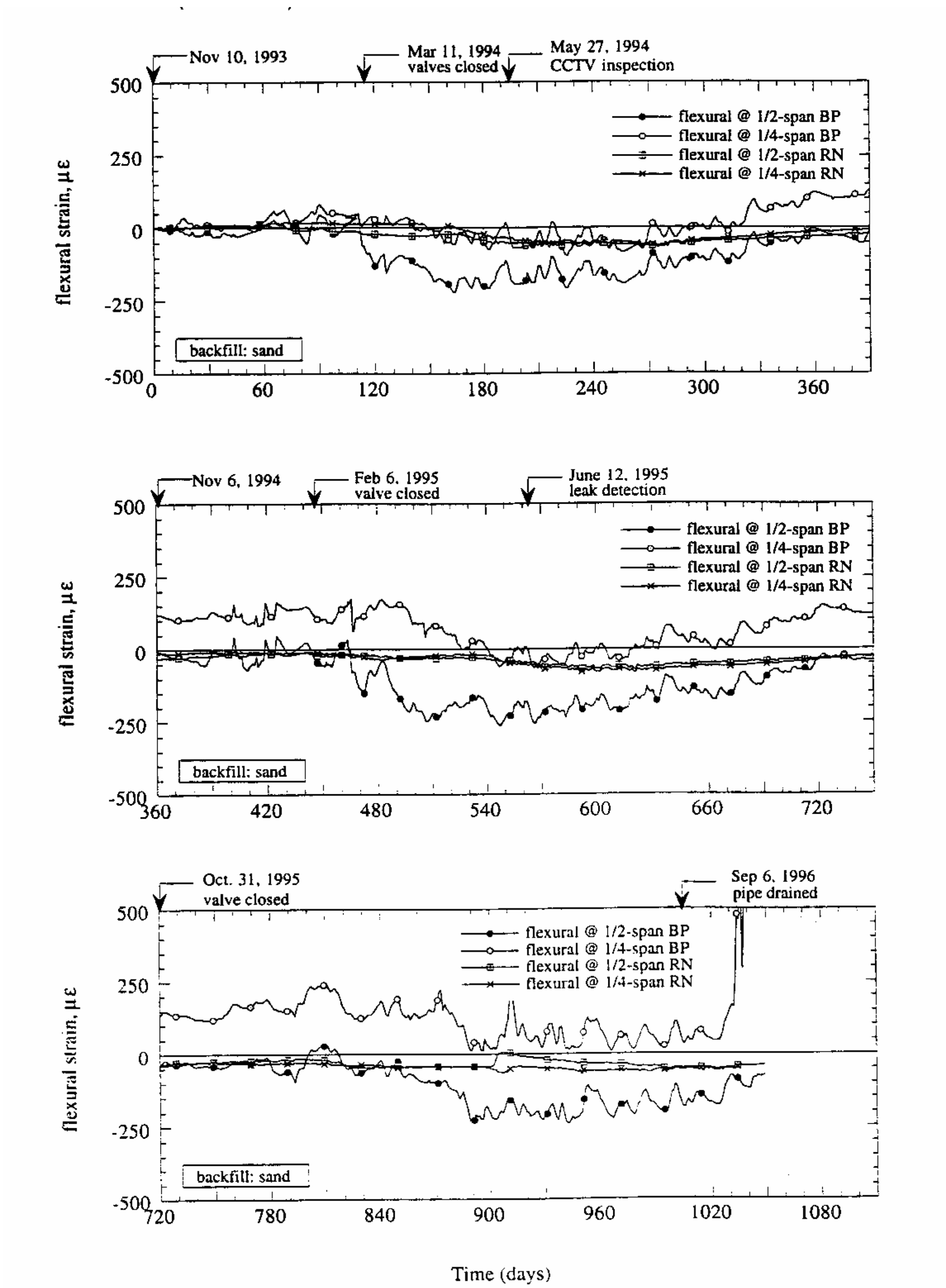

Figure 23 - Flexural strain histories of bypass (BP) and renewal (RN) PVC pipes buried in unshrinkable fill (section B) : 1993-1996

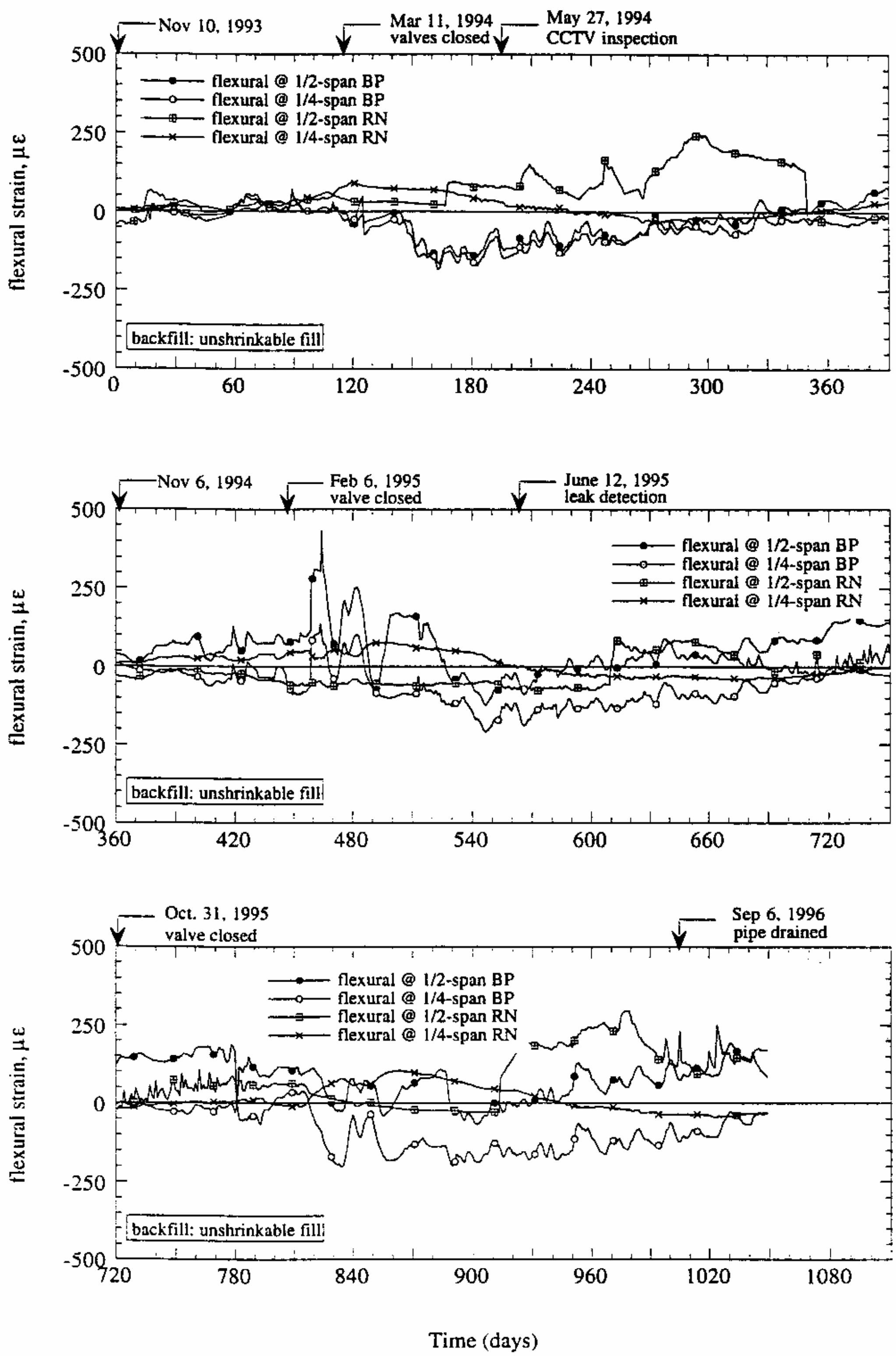

Figure 24 - Hoop strain histories of bypass (BP) PVC pipes buried in native clay (section B) : 1993-1996

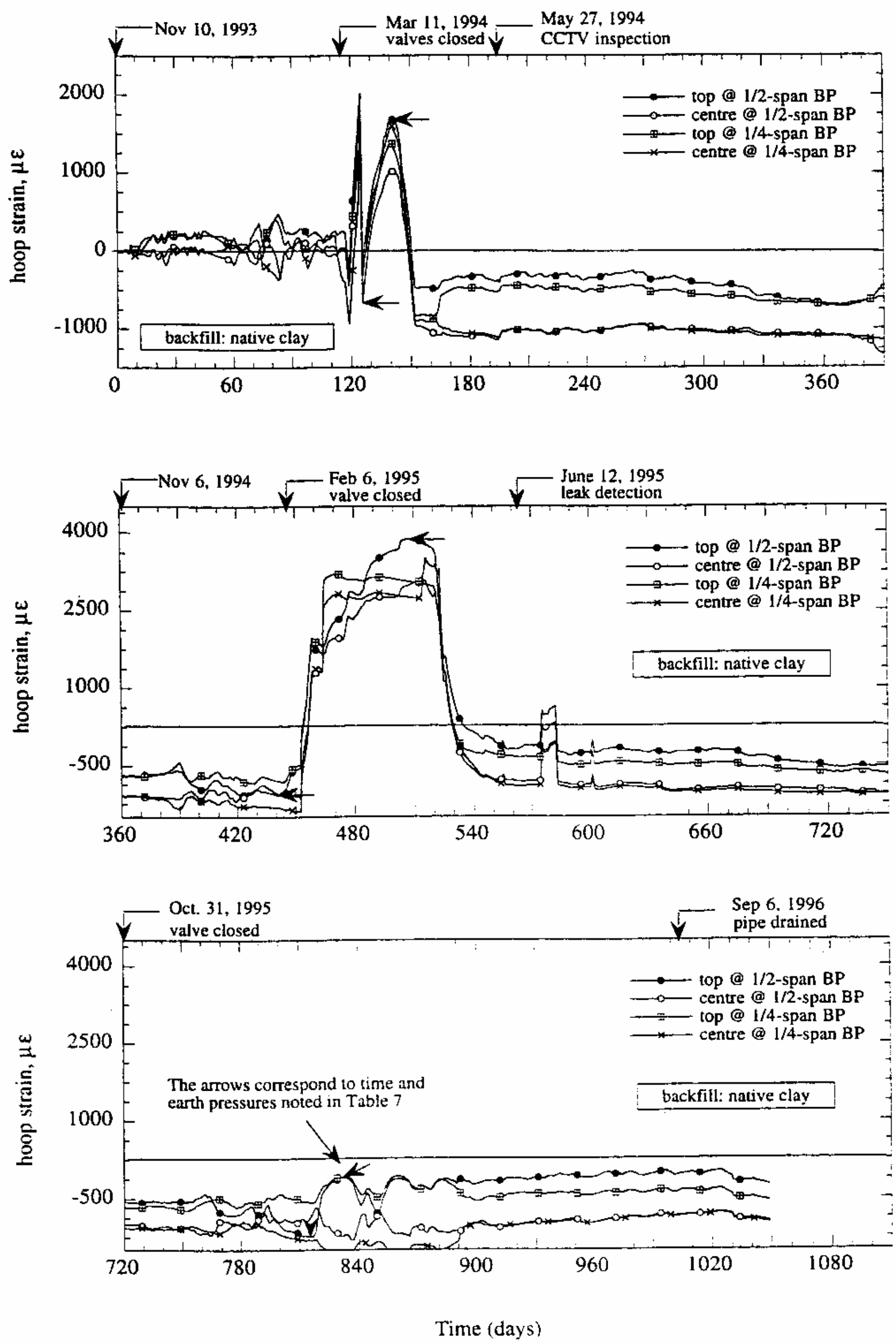

Figure 25 - Hoop strain histories of bypass (BP) PVC pipes buried in clean sand (section C) : 1993-1996

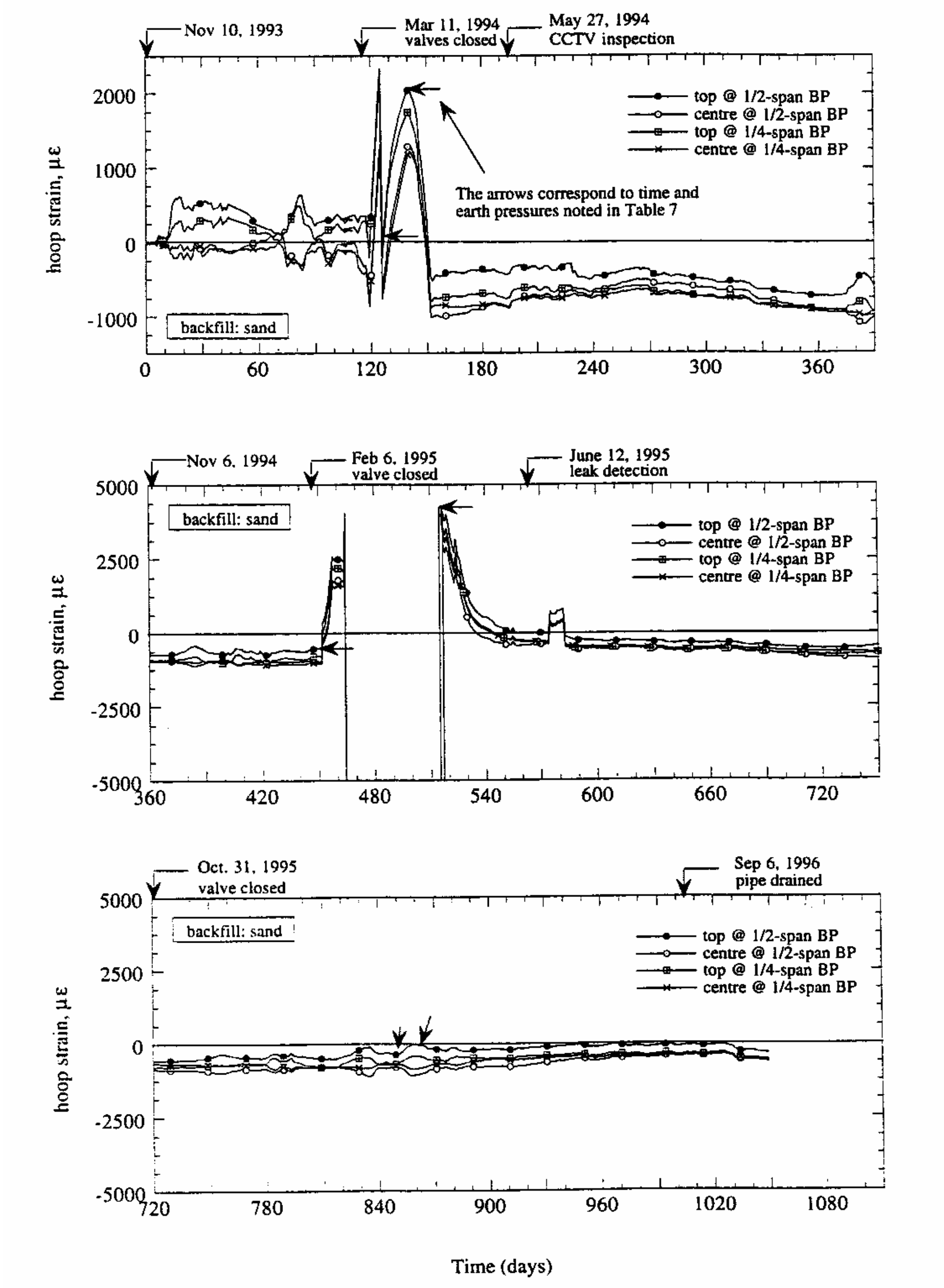

Figure 26 - Hoop strain histories of bypass (BP) PVC pipes buried in unshrinkable fill (section D) : 1993-1996

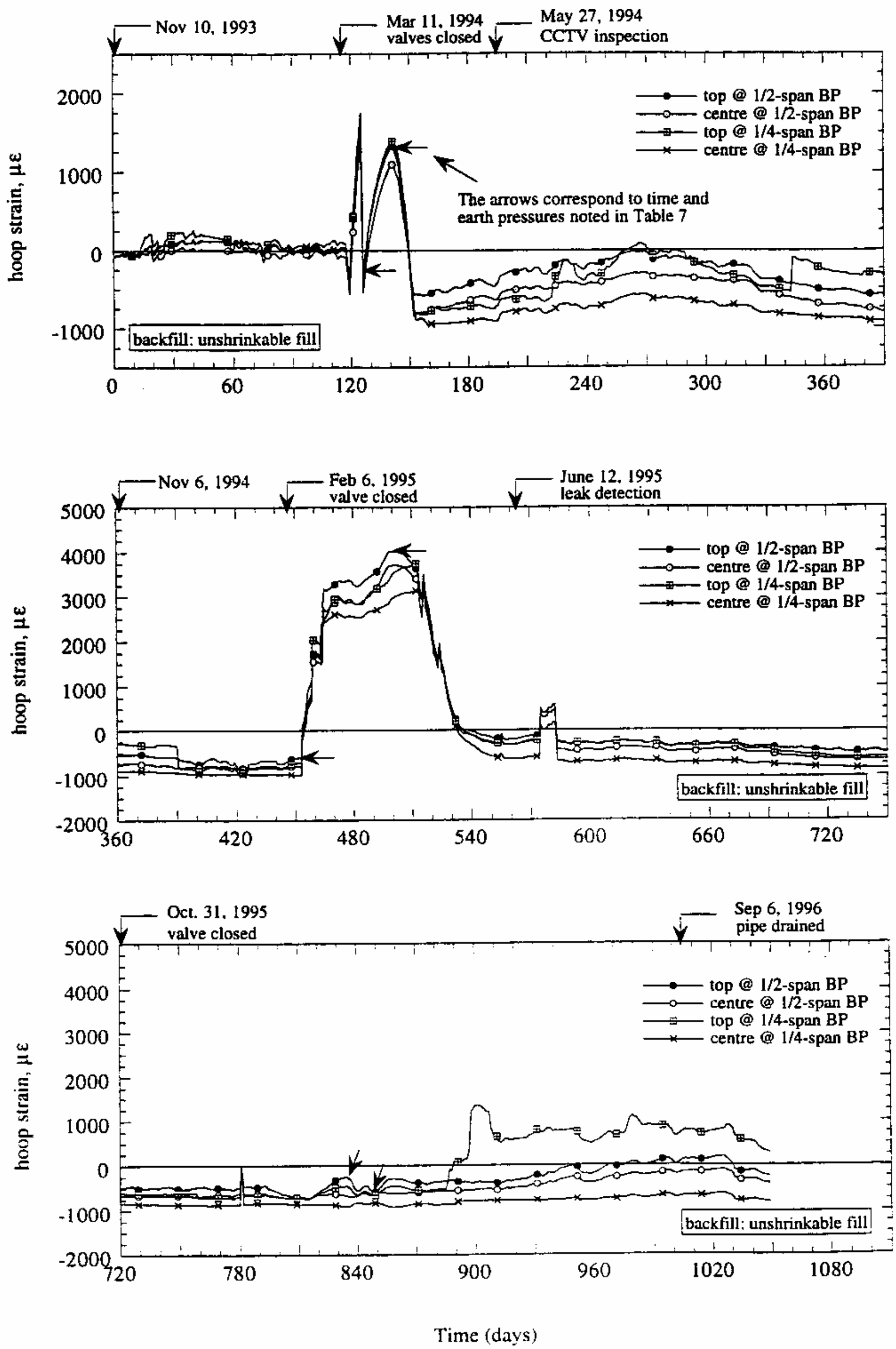

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Figure 27 - Hoop strain histories of renewal (RN) PVC pipes buried in native clay (section B) : 1993-1996

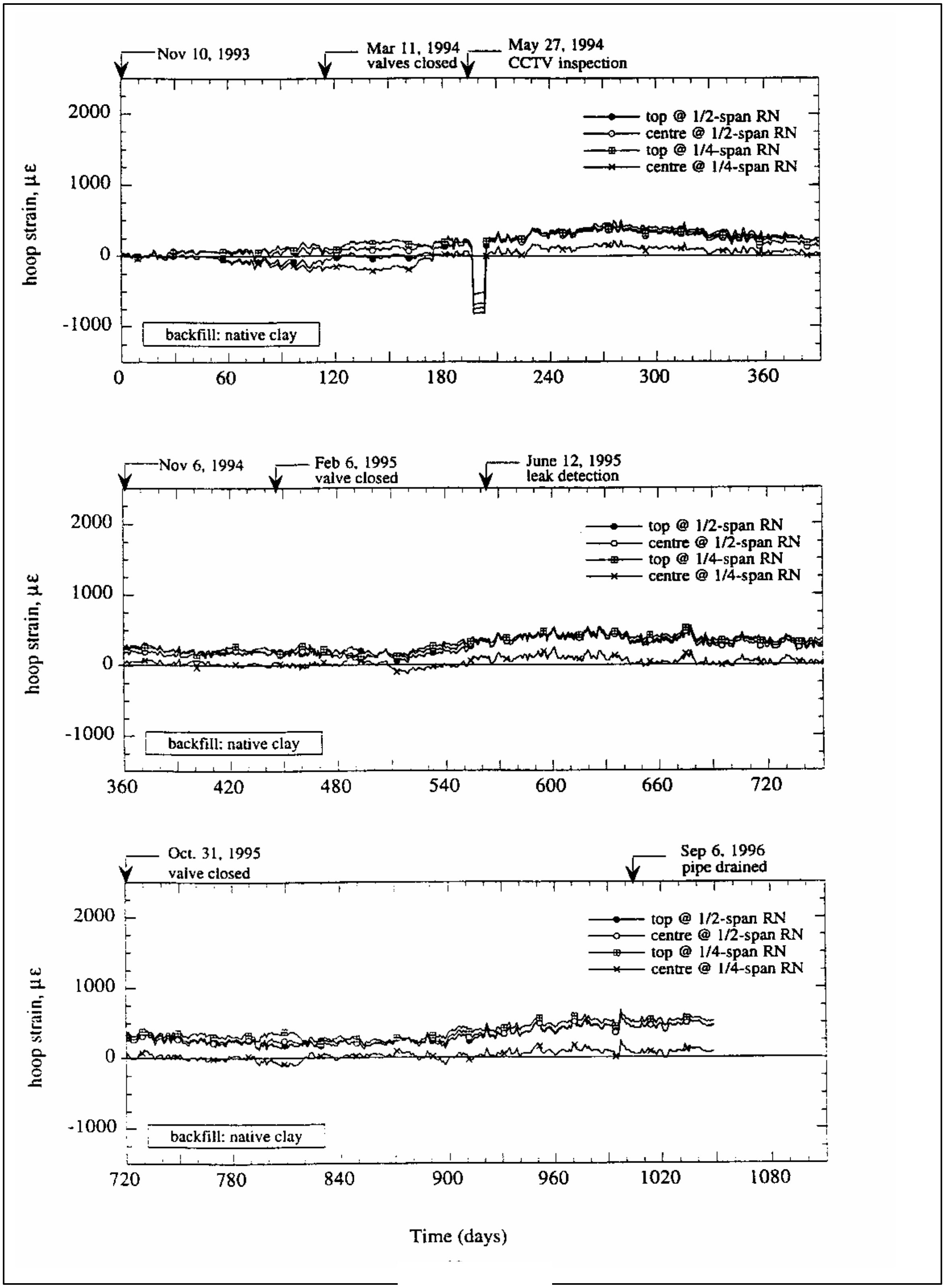

Figure 28 - Hoop strain histories of renewal (RN) PVC pipes buried in clean sand (section C) : 1993-1996

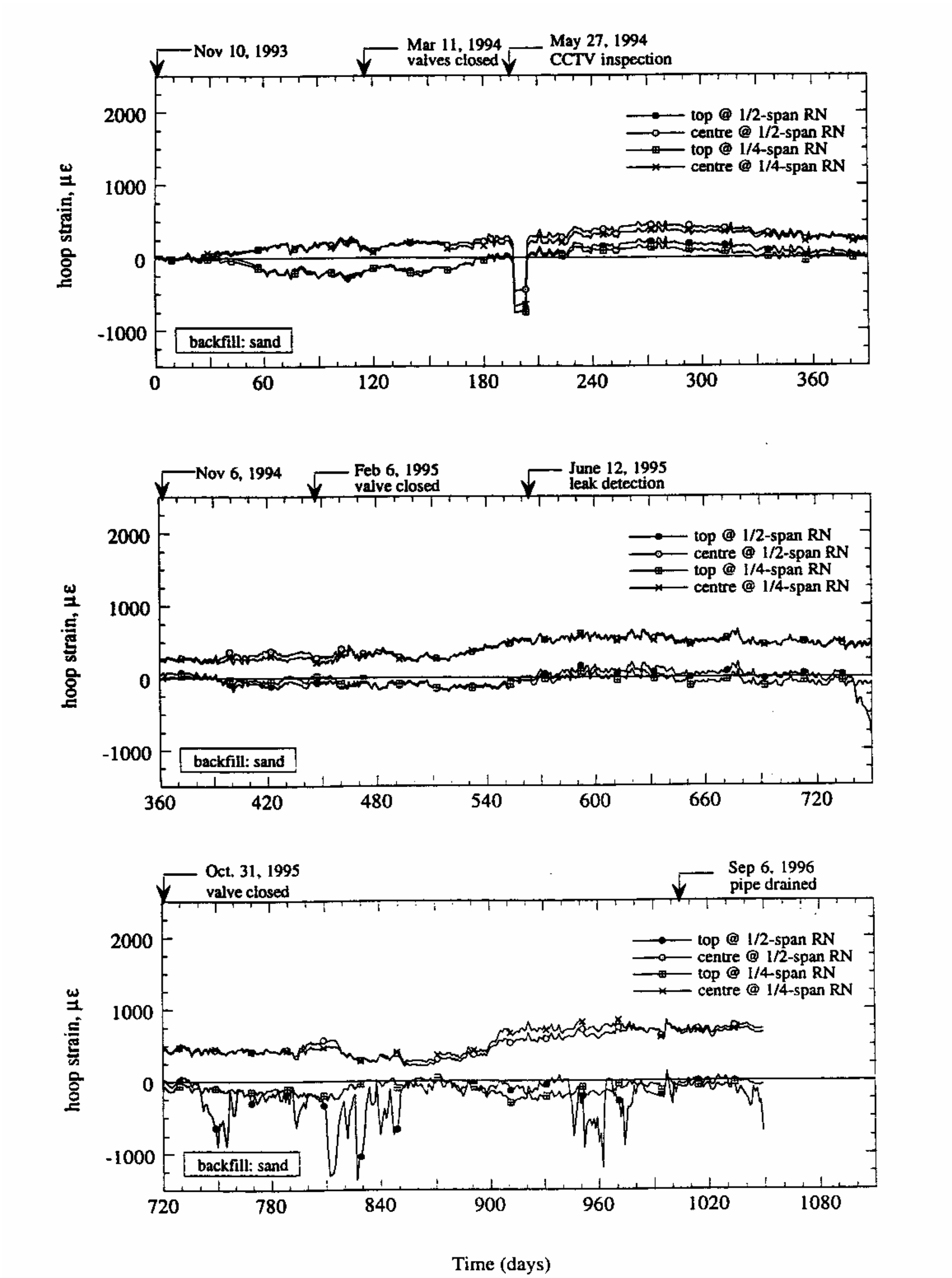

Figure 29 - Hoop strain histories of renewal (RN) PVC pipes buried in unshrinkable fill (section D) : 1993-1996.