Canada-France
Pipeline - Ground Freezing Experiment:
Frozen Transition Experiment

First Freeze Period
and
Pipe Relaxation Period

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Report to

Terrain Sciences Division,
Geological Survey of Canada,
Energy, Mines and Resources Canada

and to
ESSO RESOURCES CANADA LIMITED

FOOTHILLS PIPE LINES LTD.

INTERPROVINCIAL PIPE LINE INC.

NOVA CORPORATION OF ALBERTA

TRANSCANADA PIPELINES LIMITED
on behalf of THE POLAR GAS PROJECT

SHELL CANADA LIMITED

YUKON PACIFIC CORPORATION

May 1992

Foreword

This report covers the first operating phase of the new experiment at Caen. The details of pipe behaviour were different from previous experiments, since the frost heave on the freezing side of the experiment was concurrent with thaw settlement on the prefrozen side. While this was not anticipated, and while it is unlikely to occur in nature, the experimental observations are still of great interest and value in analyzing pipe-soil interactions and validating models. The results may be of particular value for situations involving artificial ground freezing. With the commencement of the second freeze cycle, steps have been taken to ensure more stable conditions on the prefrozen side.

In October 1991 a seminar was held in both Caen and Paris, giving an opportunity for the various sectors concerned with eventual pipeline development - consultants, regulators, those concerned with finance and investment - to meet with the engineers and scientists. The detailed arrangements of the seminar were undertaken by our French partners, and proceedings of the seminar are now in preparation. More recently, lecture presentations have been made and publications have appeared covering various aspects of the earlier experiments at Caen (Williams 1992, Williams et al. 1992).

As usual, it is important to note the indispensable role of our French colleagues in making possible the project as a whole. We would particularly note the contributions of M. Andre Dupas and M. René Dumoulin. The assistance of the Director of the Centre de Geomorphologie where the Station de Gel is located and members of his staff is also appreciated as is the continuing smooth cooperation with the Laboratoire Central des Ponts et Chaussées and the Centre National de la Recherche Scientifique.

The field project managers for the period covered by this report were Joan Watton for the Canadian team, and Marie-Christine Delhomme for the French team. This report was prepared by Dan Riseborough, Ottawa project manager.

Liaison with the seven sponsoring companies:

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has been maintained through John Ellwood of Foothills, with technical advice from Derrick Nixon (Esso Resources). Liaison with Energy Mines and Resources Canada is through Dr. Alan Judge. The help of all these is appreciated. The project is supervised by a Scientific Committee whose members are listed below.

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Introduction

This report describes work undertaken in the second year of a three year ground freezing experiment being carried out in Caen, France.

The aim of the experiment is to examine the forces exerted on a buried gas pipeline crossing a boundary between permafrost and unfrozen, frost-susceptible ground. Crossing a vertical thermal interface of this type is expected to be the worst case frost heave design scenario for gas pipelines buried at high latitudes. When such a pipeline is operated at freezing temperatures, soil freezing around the pipe on the initially unfrozen side of the transition will induce frost heave. (On the permafrost side of the transition, ice segregation or continuing frost heave will be present, but will be significantly less.) Adhesion of frozen material to the pipe and cohesion of the frozen soil mass will anchor the pipe in the permafrost. Differential frost heave combined with the resistance to pipe uplift on the frozen side will result in bending stresses in the pipe. At the same time, the resistance of the pipe to bending will transfer stresses to the soil, which will alter the thermodynamic conditions governing the process of ice segregation. This experiment is concerned primarily with an examination of this interdependence of pipe and soil behaviour.

Summary of experiment

The test facility (a cold room 8 m wide by 18 m long) was filled to a depth of 2.3 m with Caen silt, a frost susceptible soil. An insulating thermal wall was erected at the ground surface to divide the facility and soil into two sections whose temperature could be separately controlled. The soil on one side of the wall was frozen as rapidly as possible, to a depth of at least 2 metres. A pipe trench was excavated as soon as the frost depth was sufficient to permit traffic on the trench floor. A 16 m long, 273 mm diameter steel pipe was placed in the trench at a depth to the top of the pipe of approximately one pipe diameter and backfilled. The backfill was allowed to freeze in place on the prefreezing side. At the start of the freezing experiment, (9:35 a.m., June 26 1991) the thermal wall was removed, whereafter air temperature in the cold room was maintained at -0.75°C. Pipe circulation temperature was maintained at -5°C for the first 215 days of the freeze cycle, after which it was lowered to -8.5°C (on January 27 1992), to accelerate frost penetration for the last 42 days of the freeze.

On March 9 (day 257), pipe circulation temperature was increased to +5°C, while surface temperature was maintained at -0.75°C, to allow thaw to occur around the pipe while otherwise maintaining freezing conditions in the ground, as an experiment in pipe relaxation. This is called the "relaxation period" throughout this report.

On March 22 (day 270), pipe circulation was shut down and the insulating wall separating the prefrozen and initially unfrozen sides of the experiment was completed (the wall had been partially reconstructed during the pipe relaxation period). This phase of the experiment is called the "transitional phase", during which the temperatures in the facility were maintained at +5°C on the initially unfrozen side (to initiate thaw), and at -5°C on the prefrozen side (to reestablish deeper frost).

Table 1 provides a timetable of significant dates in the experiment.

Instrumentation

The soil thermal and hydrological regimes, internal soil pressures, soil movement and expansion, pipe movement and pipe deformation are monitored using a variety of instruments and techniques, summarised in Table 2.

These devices and techniques were described in detail in the first report for this project (Geotechnical Science Laboratories, 1991). Figure 1 shows a plan view of the experiment, with sensor locations keyed to Table 3.

Table 1 Significant Dates in the Experiment

Event	Date	Days elapsed from 26-Jun-91
Soil all placed	28-Sep-90	-271
Wall placed	24-Oct-90	-245
Pre-freezing Starts @ -3	01-Nov-90	-237
Pre-freezing @ -8	12-Nov-90	-226
Pre-freezing @ -15	08-Dec-90	-200
Pre-freezing @ -18	15-Jan-91	-162
Trench excavation	06-Feb-91	-140
Pipe placement	02-Apr-91	-85
Backfill cold side	26-Apr-91	-61
Pre-freezing @ -8	26-Apr-91	-61
Backfill warm side	29-May-91	-28
Pre-freezing @ -4	12-Jun-91	-14
Freezing experiment starts	26-Jun-91	0
Pipe temperature lowered to -8.5	27-Jan-92	215
Pipe relaxation begins	09-Mar-92	257
Relaxation ends: transition begins	22-Mar-92	270
Soil columns all installed	11-Jun-92	351
Transition ends; Second freeze starts	01-Jul-92	371

Table 2 Instrumentation used in the Experiment

Thermal regime:	- thermistor strings in the soil - thermistors on pipe surface - thermocouples to monitor air temperature (in pipe and in chamber).
Hydrological regime:	- monitoring of water inputs - piezometer wells to monitor water table
Pressure measurements:	- EPC total earth pressure cells - Petur/RST total pressure cells - Glotzl total pressure cells
Soil movement/expansion:	- Optical surface surveying - Magnet heave measurement system - Bison soil strain gauges - Hydrostatic profiler (for soil movement beneath pipe)
Pipe movement:	- Optical survey of pipe survey rods
Pipe deformation:	- strain gauges
Pipe- soil interaction:	- "LVDT" longitudinal pipe-soil shear device - flexible steel strip soil shear device. - wooden disc vertical shear columns.

Schedule of measurements

During the early stage of the experiment, most manual measurements (pressure, strain, heave) were taken 2 times per week, with optical levelling once per week. During the thaw relaxation period, optical surveys of the pipe axis were taken every two to three days. Thermistor measurements were recorded via datalogger every 6 hours throughout the experiment. The strain gauge datalogger was activated at the same frequency as the manual measurements, during which measurements were recorded once per minute for about an hour to monitor stability.

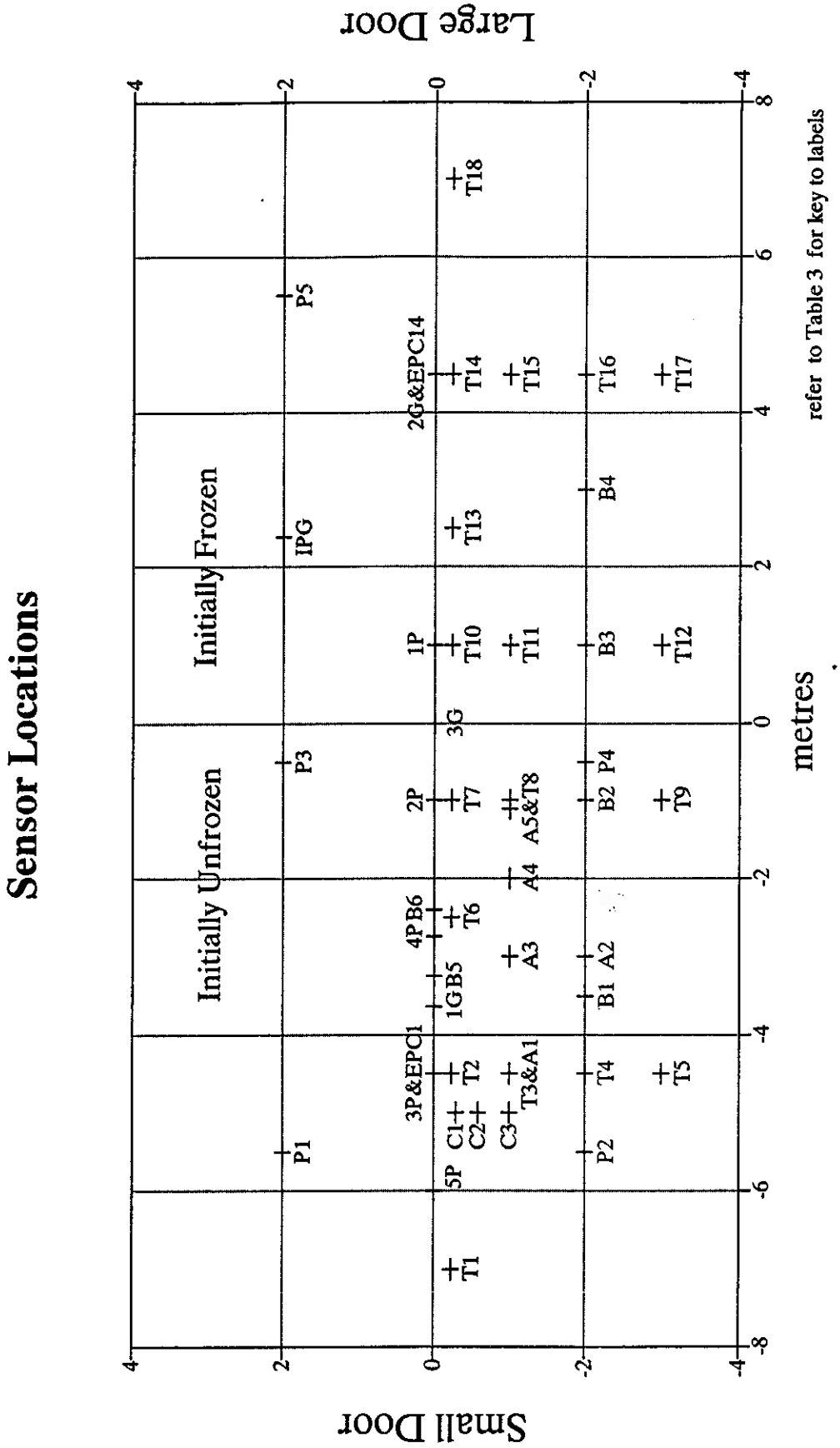

Sensor Locations
Initially Unfrozen
Initially Frozen
Small Door
Large Door
metres
refer to Table 3 for key to labels
T1
5P
C1+
C2+
C3+
P1
3P&EPC1
T2
T3&A1
1GB5
4P B6
T6
A3
A4
A5&T8
P3
2P
T7
3G
1P
T10
T11
IPG
T13
2G&EPC14
T14
T15
P5
T18
P2
T4
T5
B1 A2
B2 P4
T9
B3
T12
B4
T16
T17

Figure 1

Table 3 Sensor Locations

Device	Site	Distance Off Axis (m)	Axial Distance (m)
Bison Cells	B1	-2.00	-3.50
	B2	-2.00	-1.00
	B3	-2.00	1.00
	B4	-2.00	3.00
	B5	0.00	-3.25
	B6	0.00	-2.40
Magnet Rings	A1	-1.00	-4.50
	A2	-2.00	-3.00
	A3	-1.00	-3.00
	A4	-1.00	-2.00
	A5	-1.00	-1.10
Petur total pressure cells	1P	0.00	1.00
	2P	0.00	-1.00
	3P	0.00	-4.50
	4P	0.00	-2.75
	5P	0.00	-6.00
Glotzl total pressure cells	1G	0.00	-3.63
	2G	0.00	4.50
	3G	0.00	0.00
EPC pressure cells	EPC1	0.00	-4.50
	EPC14	0.00	4.50
Thermistor cable sites (cables are interchangable between sites)	T1	-0.25	-7.00
	T2	-0.25	-4.50
	T3	-1.00	-4.50
	T4	-2.00	-4.50
	T5	-3.00	-4.50
	T6	-0.25	-2.50
	T7	-0.25	-1.00
	T8	-1.00	-1.00
	T9	-3.00	-1.00
	T10	-0.25	1.00
	T11	-1.00	1.00
	T12	-3.00	1.00
	T13	-0.25	2.50
	T14	-0.25	4.50
	T15	-1.00	4.50
	T16	-2.00	4.50
	T17	-3.00	4.50
	T18	-0.25	7.00
Wood columns (horizontal shear	C1	-0.30	-5.00
	C2	-0.60	-5.00
	C3	-1.00	-5.00
Frost tube	IPG	2.00	2.40
Piezometer wells	P1	2.00	-5.50
	P2	-2.00	-5.50
	P3	2.00	-0.50
	P4	-2.00	-0.50
	P5	2.00	5.50

Results

Overall behaviour

During the initial 215 days of the freezing period, the behaviour of the soil and the pipe was dominated by freezing and frost heave on the initially unfrozen side of the experiment, and by thawing at the base and subsequent settlement of the pre-frozen side. The thawing on the prefrozen side was due to the difference in surface temperatures maintained during the period of prefreezing and during the experiment. The steep temperature gradient between the surface and the base of the experimental basin which had been maintained during the prefreeze was not maintained during the experiment, thereby reducing the rate of heat extraction which had sustained the deep frostline on the prefrozen side prior to the initiation of the experiment.

Frost penetration was considerably slower in this experiment than in the previous experiments at Caen under similar operating temperatures, due to the insulation provided by the plastic wrapping on the pipe (absent in the earlier experiments). The addition of the short section of pipe for the pullout test in the pipe circulation loop may have contributed to the difference as well, by reducing the efficiency of heat transfer as a result of the increased resistance to flow in the pipe loop.

Pipe temperatures were lowered in order to increase frost penetration for the last 42 days of the freeze cycle. During this latter period (days 215-257), frost line penetration and frost heave were accelerated on the initially unfrozen side, while on the prefrozen side thaw settlement ceased almost completely in soil close to the pipe. Thaw settlement did continue on the prefrozen side however, in the soil not influenced by the colder pipe circulation temperature.

The combination of frost heave and thaw settlement resulted in tilt of the pipe along its major axis, with the result that the stresses which developed in the pipe were lower than anticipated.

During the thaw relaxation period, the stresses in the pipe were reduced significantly as the soil around the pipe lost strength upon thawing. The pipe lost much of its curvature, although it remained significantly tilted from its initial position.

Since the initiation of the transitional period, settlement of the pipe has stopped on the prefrozen side of the experiment, and is now virtually complete on the initially unfrozen (and now completely thawed) side of the experiment.

Thermal regime

Figure 2 shows operating temperature conditions in the pipe and in the air circulating in the facility during the freeze and relaxation periods, and at the start of the transition period. Pipe temperature and circulation are controlled by a fan and compressor system mounted inside the cold room. The system incorporates a mechanism to reverse the direction of flow in the pipe, since the difference in temperature between air entering and leaving the pipe is about 2C°. The direction of circulation is reversed every six hours to maintain a uniform daily average pipe temperature. Figure 3 shows pipe temperatures (interior and exterior)

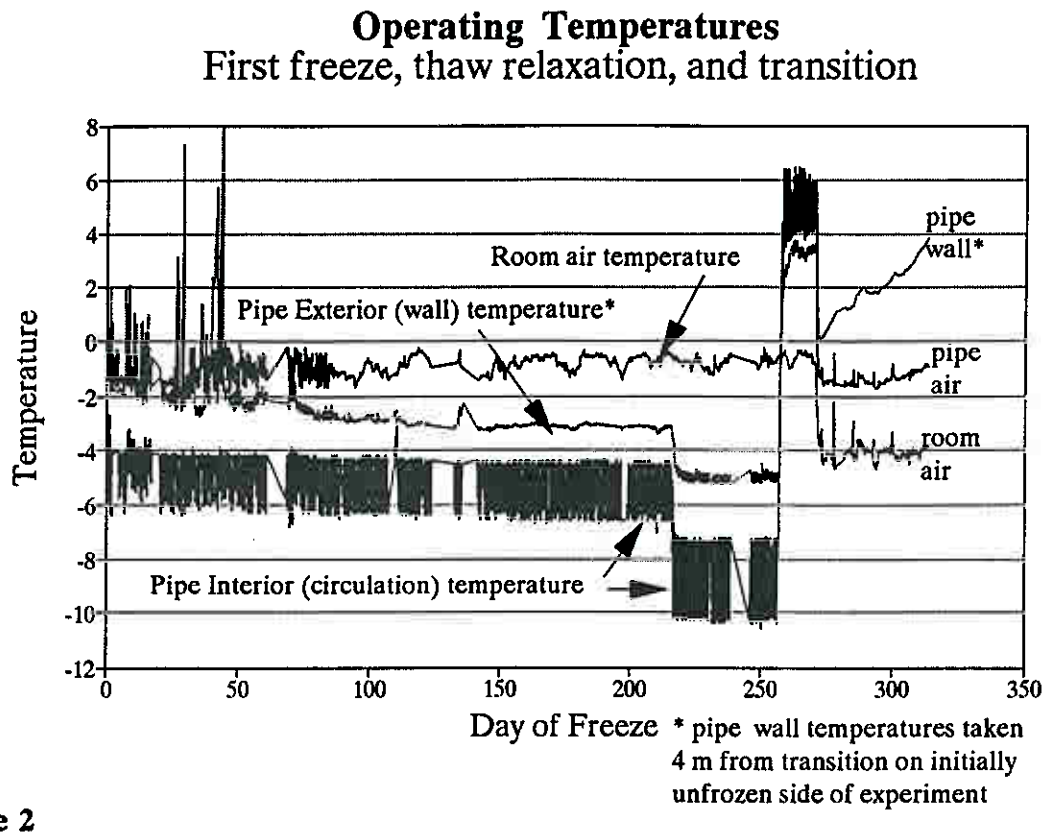


Figure 2

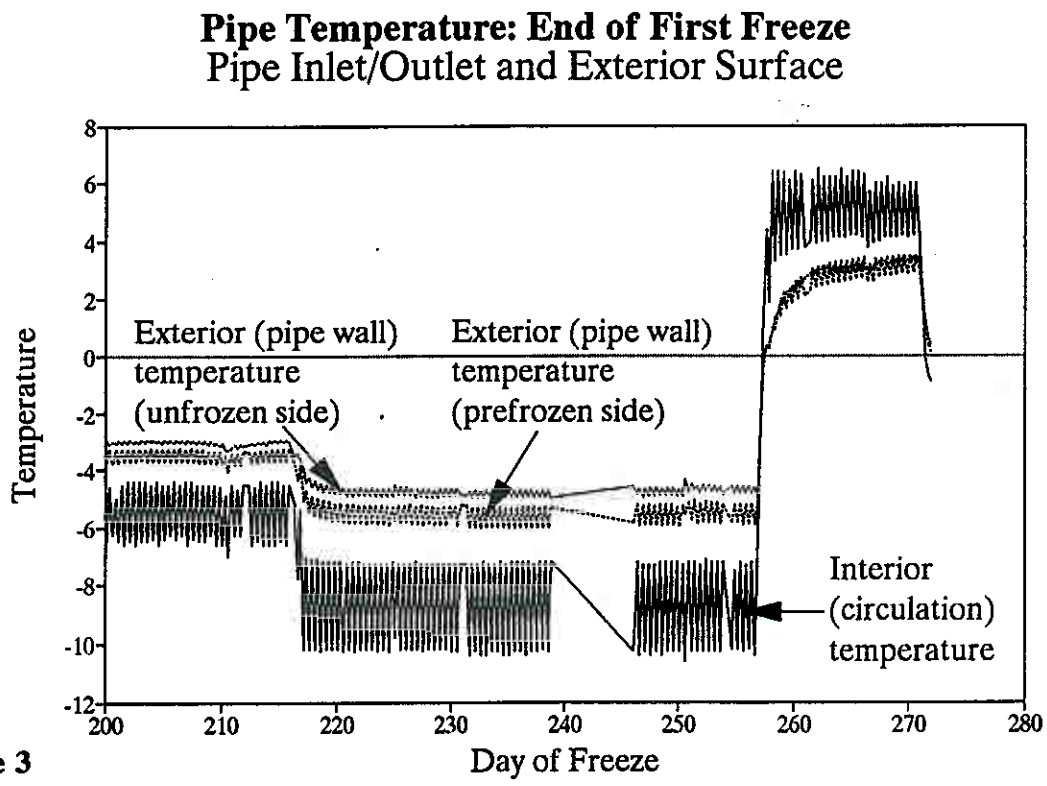


Figure 3

toward the end of the freeze and during the relaxation period.

Figure 4 shows frost line progression determined from thermistor strings adjacent to the pipe. Thaw began quickly at the base of the prefrozen material (thermistor strings did not extend below 1.9 metres), and has not yet been totally arrested. Thaw beneath the pipe has been most rapid at the margins of the prefrozen material. In the initially unfrozen material, the presence of already frozen material allowed more rapid frost penetration closer to the frozen interface (about 20 cm more frost at 1 m from the transition than at 7 m from the transition).

During the colder period at the end of the freeze, the frost line penetrated by approximately 15 cm on the initially unfrozen side, or about 25-35% of the total penetration beneath the pipe. During this period thaw at the base of the pipe was slowed but not arrested.

Frost line regression began quickly with the initiation of the relaxation period, with complete thaw in the initially unfrozen material within about 50 days.

Figures 5 to 8 show the progression of the frost line at each of the thermistor cable cross sections, and show the influence of the pipe both in extending frost on the initially unfrozen side of the experiment and in preserving the prefrozen material. On either side of the transition, the frost line moved toward the same equilibrium position: at the margins of the experiment, the

Frost Line Depth
Along pipe axis, 25 cm from centreline

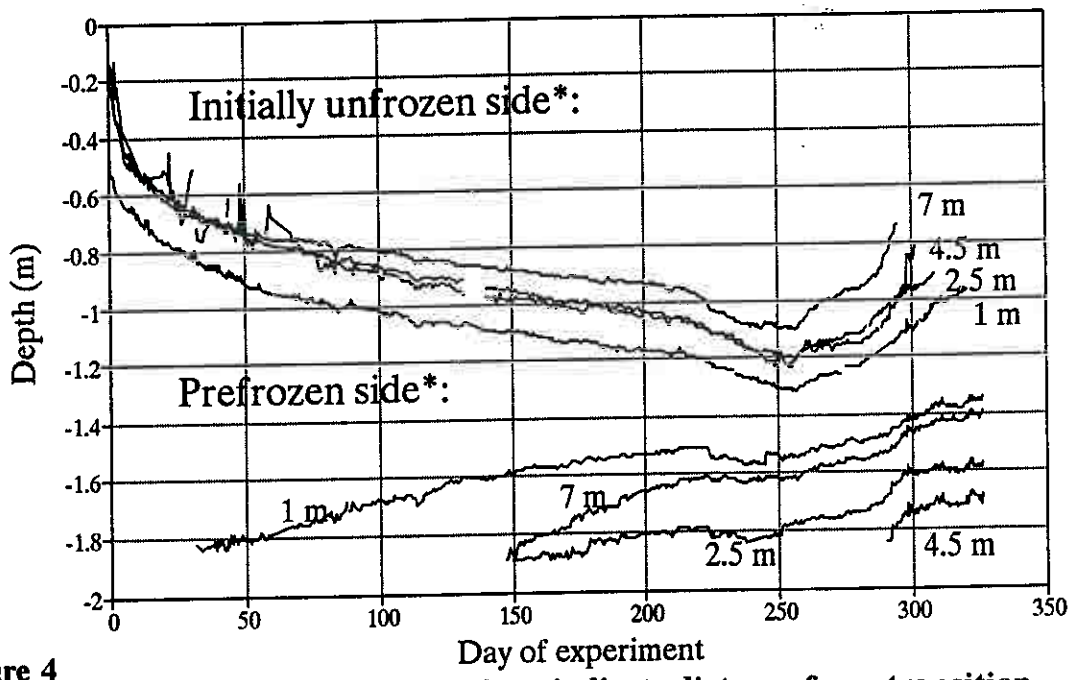


Figure 4

*** numbers indicate distance from transition**

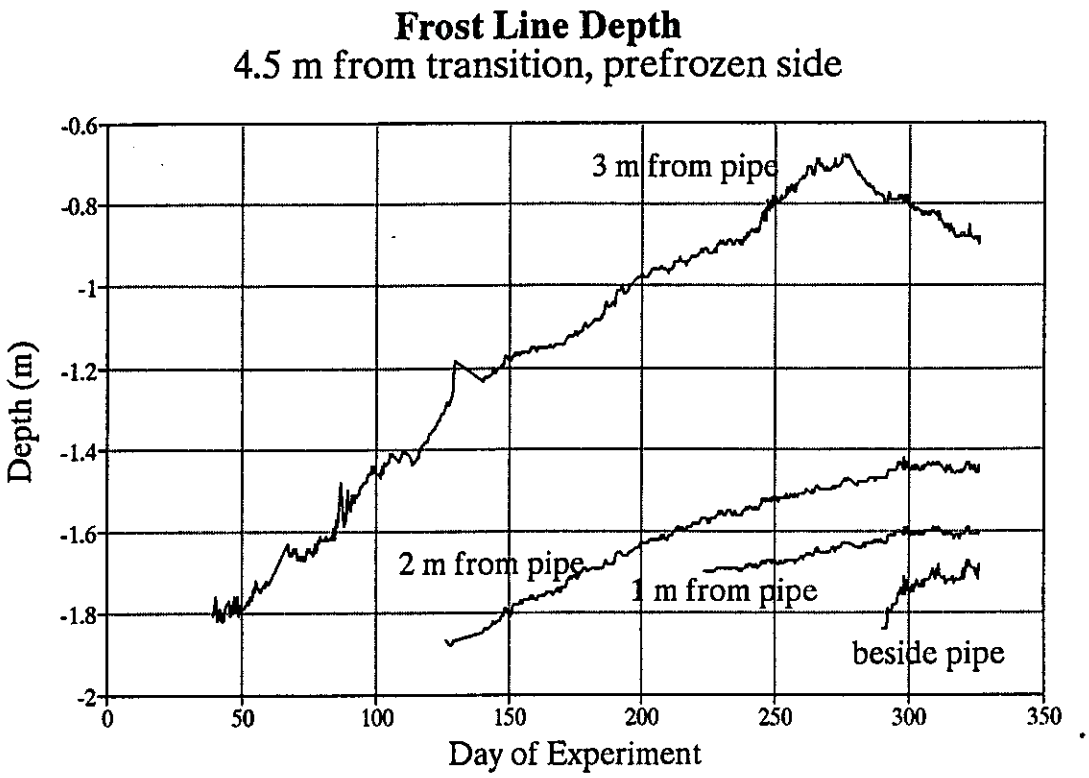


Figure 5

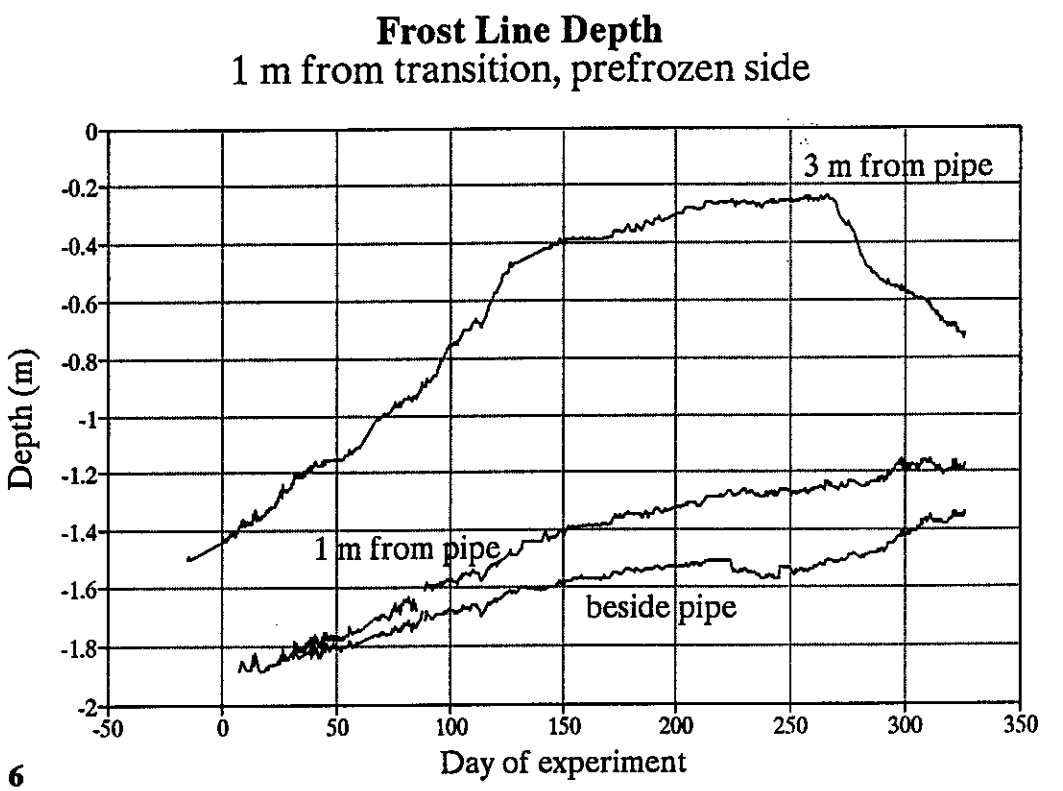


Figure 6

cm of the surface, while the frost line penetrated to about 20 cm on the initially unfrozen side. Since the initiation of the transitional phase, the frost line has deepened significantly at the margins of the prefrozen material.

Pressure measurements

All pressure sensors used in the experiment operate on the same principle: compression of an oil filled vessel forces displacement of a diaphragm within the sensor. Back-pressure is applied to the opposite side of the diaphragm to return it to its neutral position: measured back-pressure is thus equal to the pressure on the sensor.

The EPC and Glotzl cells are designed specifically for earth pressure measurements: both consist of flat steel plates welded at the periphery, with oil in between. The Petur cells are "general purpose piezometers", modified to measure total pressure. All pressure transducers are read using the same measurement instrument, designed originally for the Glotzl cells.

Earth pressure cells (EPC's)

Twelve EPC's are installed on the pipe: six on top in the prefrozen section and six on the bottom in the unfrozen section, at 0, 0.5, 1.0, 1.5, 2.5, and 3.5 m from the transition (note there are 2 EPC's at the transition). Results for these transducers are shown in Figures 9 and 10.

On the prefrozen side of the experiment, only two cells registered

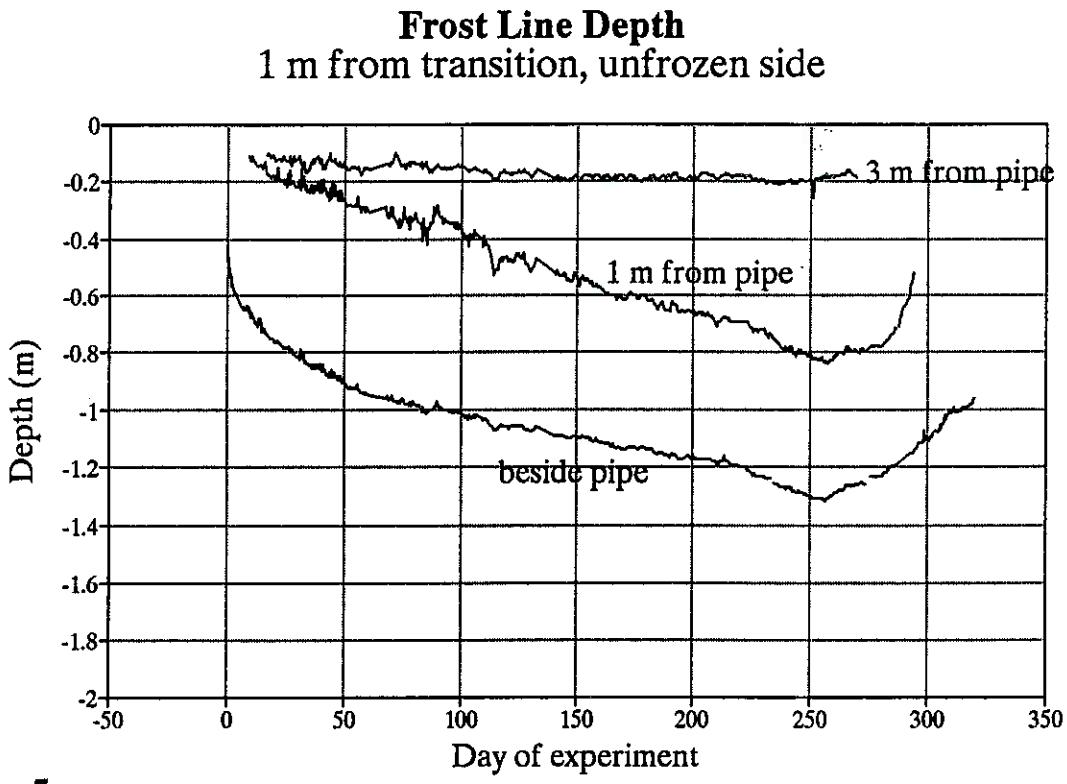


Figure 7

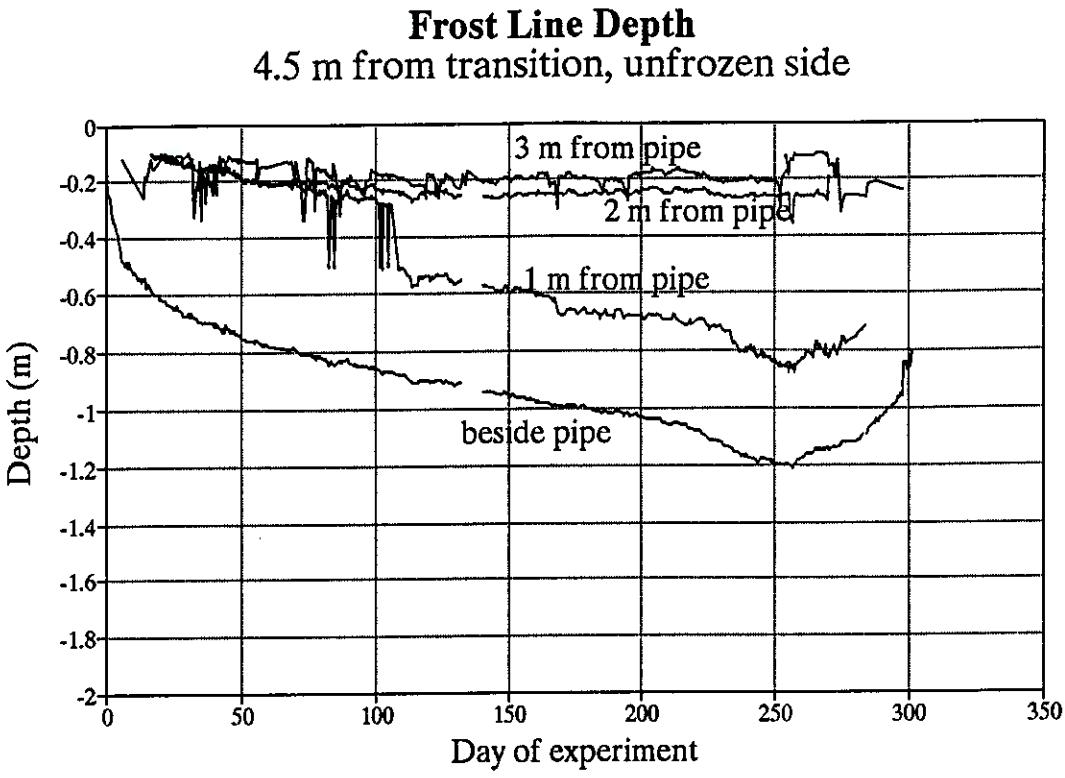


Figure 8

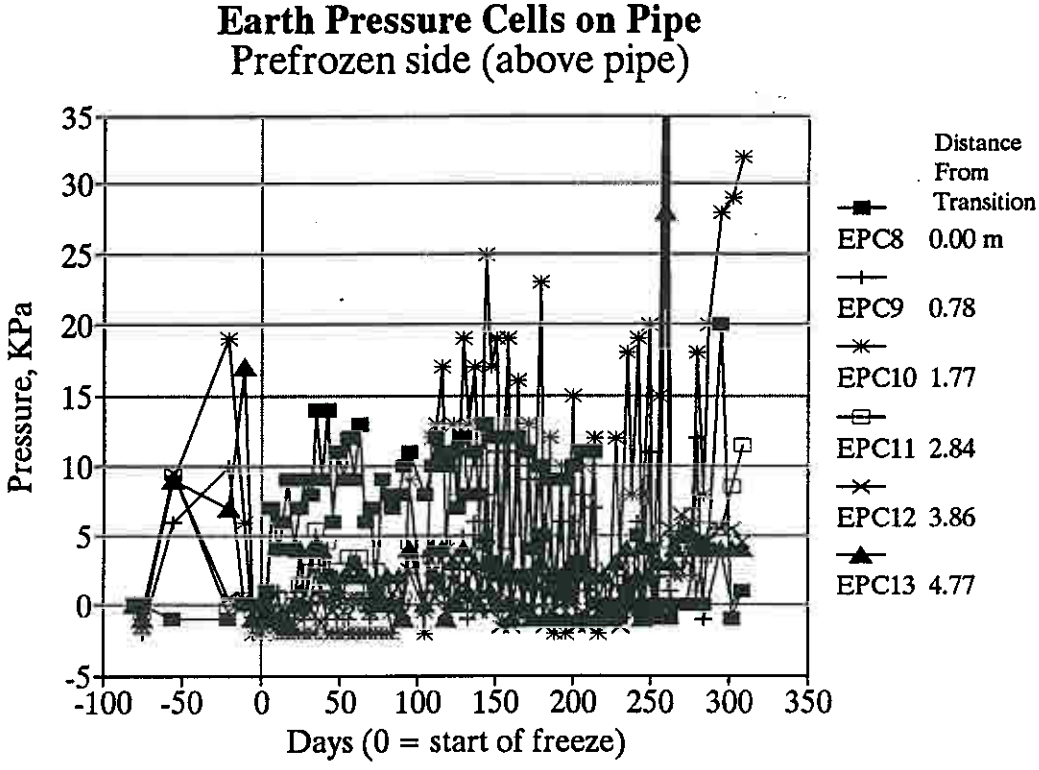


Figure 9

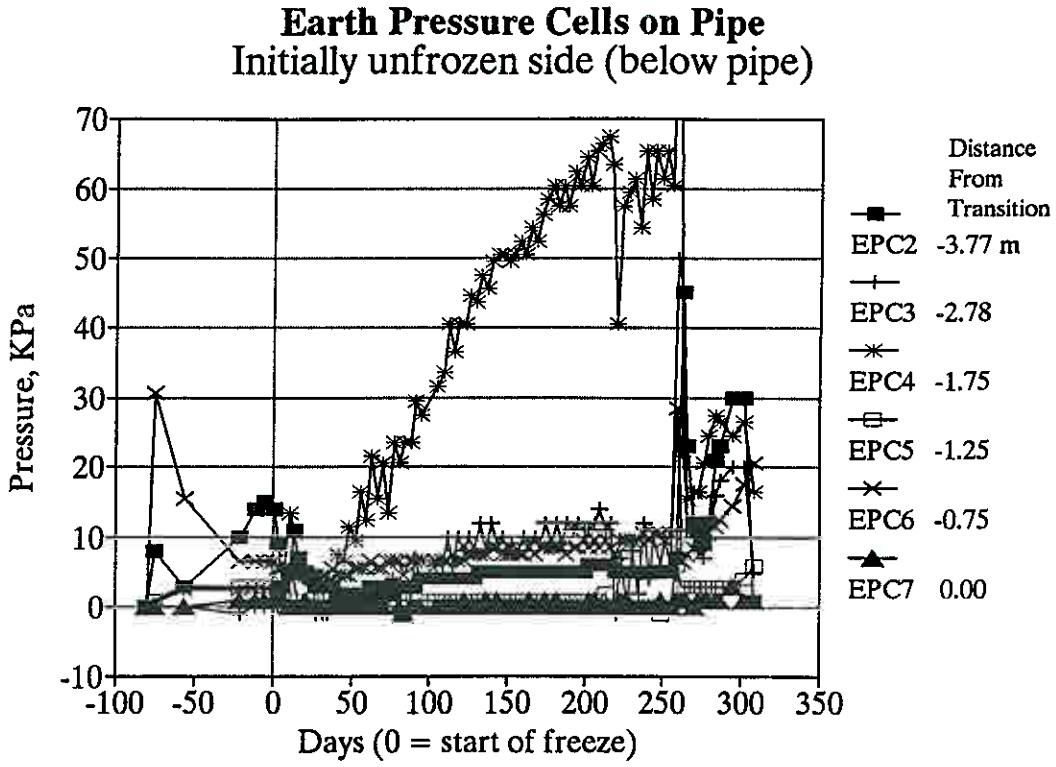


Figure 10

pressures throughout the freezing period, while on the freezing side one cell registered consistently increasing pressure. Measurements show a clearer pattern of pressures since the end of freezing, suggesting poor contact between the cells and the soil during the freeze which improved upon thawing of the soil. During the next freeze cycle, this problem is likely to recur wherever the pipe detaches from the soil as a result of arching.

Petur cells

Petur (now RST Instruments) piezometers (model P-100) are originally designed to measure pore water pressure. As delivered they are small diameter cylindrical devices (1.6 cm O.D. x 6.3 cm long), with a non-metallic filter at one end and air lines to the readout device at the other. To measure total pressure, an oil filled latex rubber bulb was placed over the filtered end, and secured using a hose clamp, taking care to exclude air from the bulb. There are five arrays of five petur cells each, all installed below the pipe, along the axis. The readings for these are shown in Figures 11-15, where the values shown represent the change from an initial reading obtained prior to the initiation of freezing. Some sensors behave inconsistently or appear to have failed during the experiment (eg 143 cm deep sensor, Figure 11), although such behaviour may be due to separation between the soil and the latex rubber bulb.

On the initially unfrozen side of the experiment, the cells respond to the passage of the frost line with an increased pressure reading, which continues to increase at a declining rate

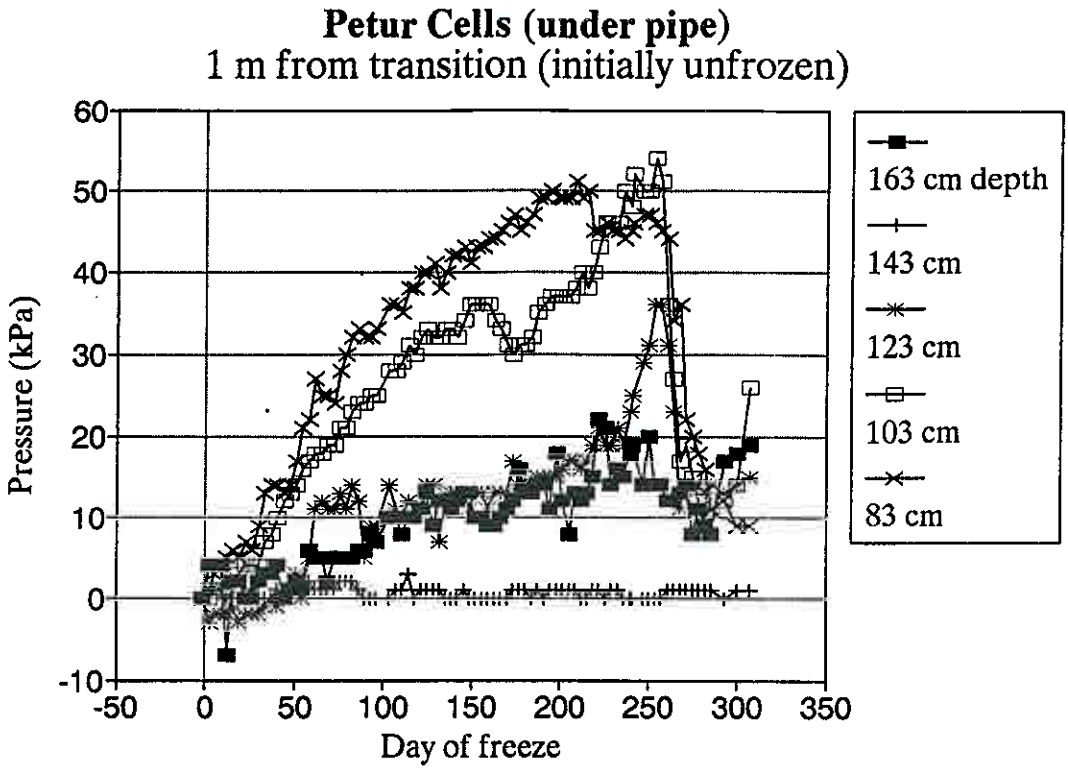


Figure 11

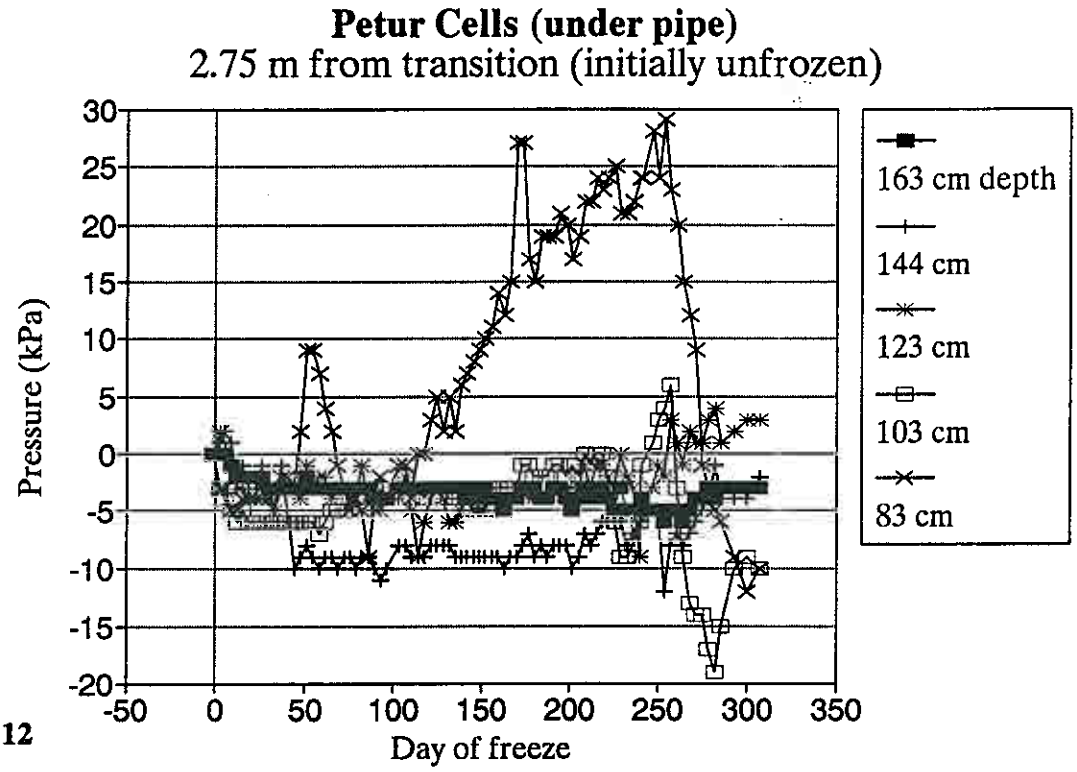


Figure 12

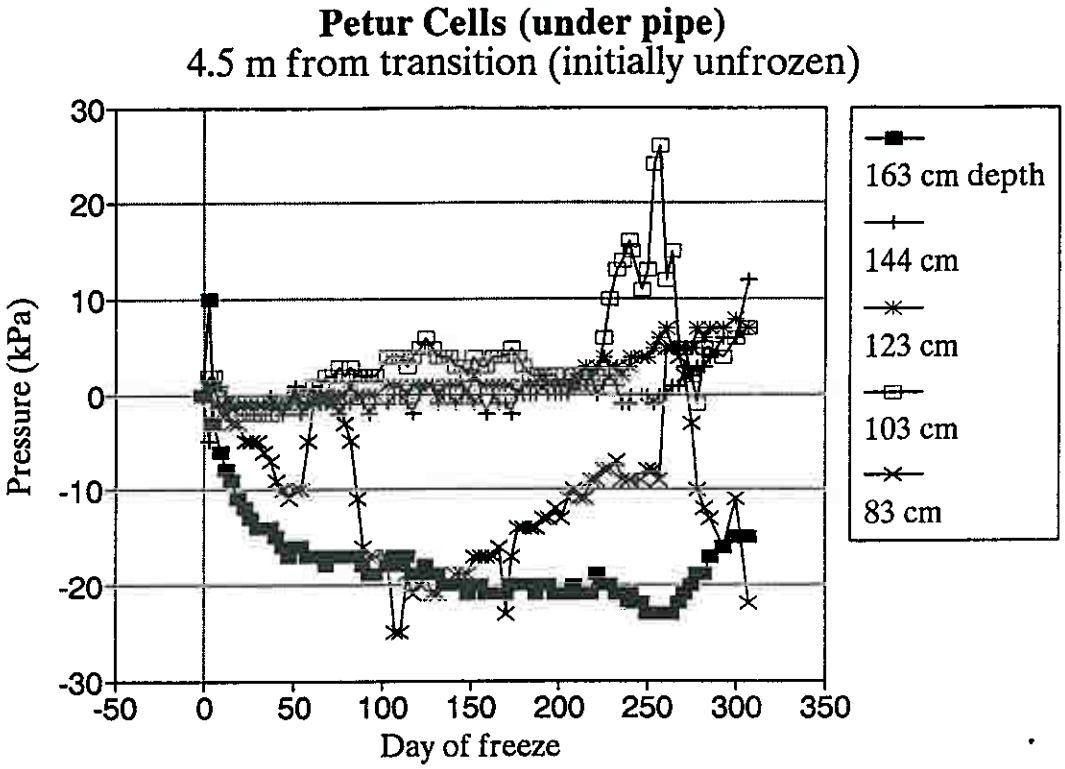


Figure 13

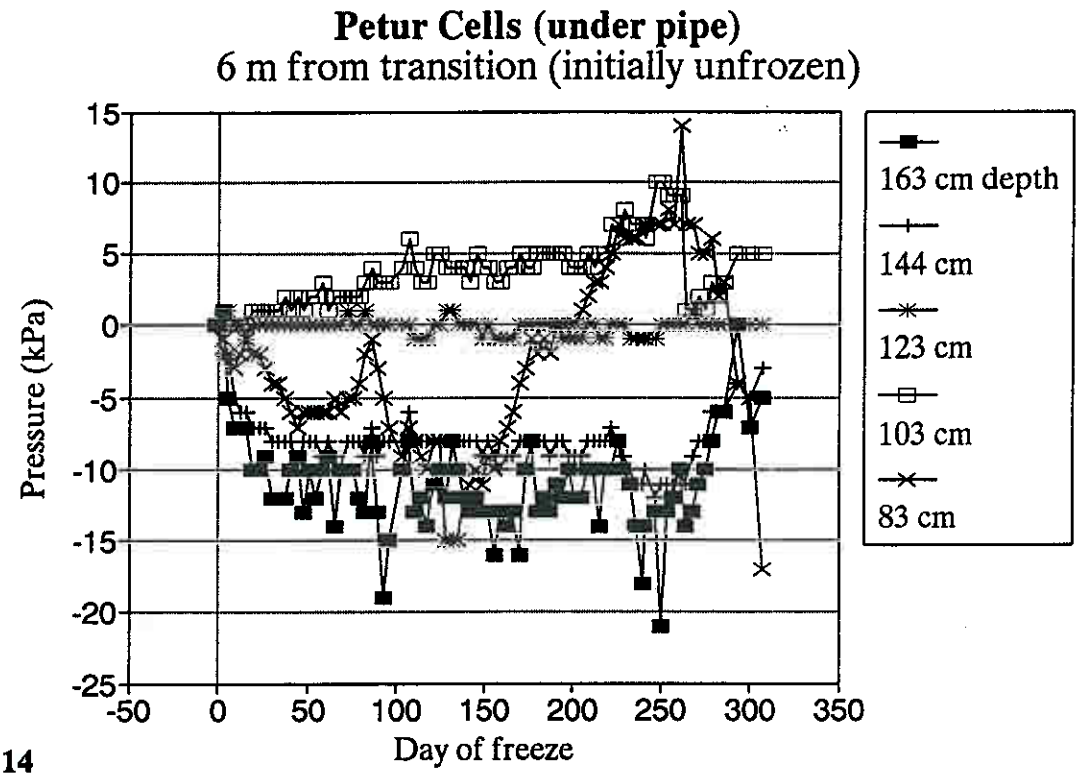


Figure 14

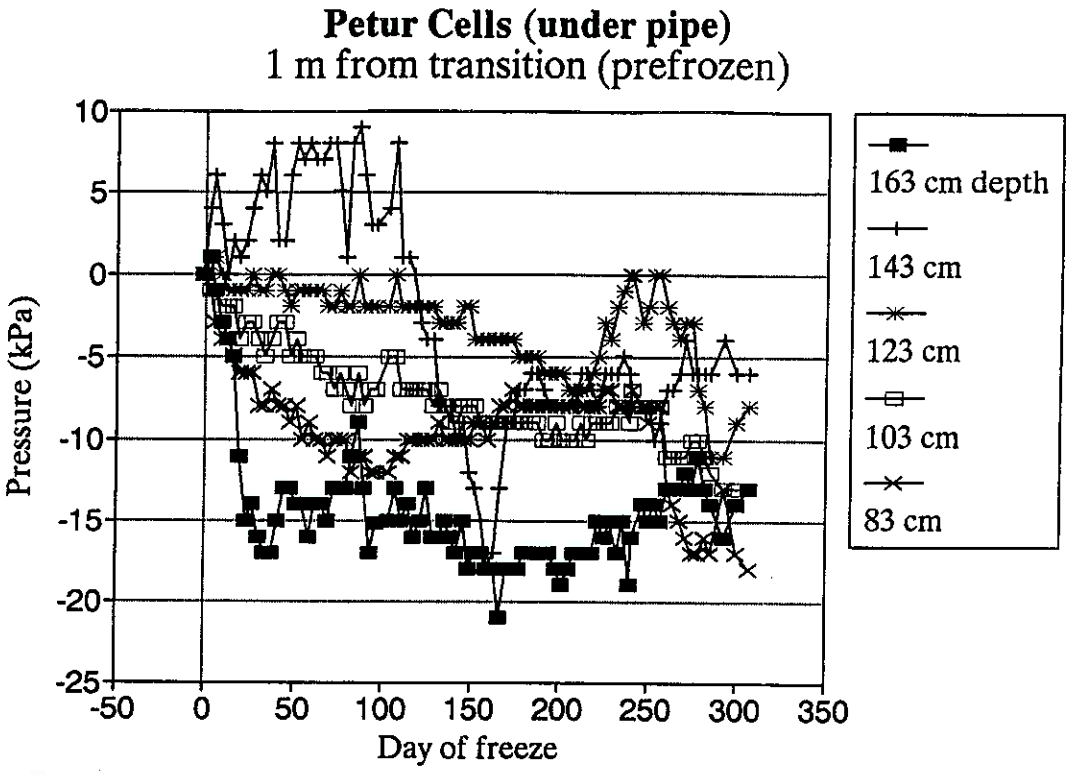


Figure 15

until the onset of thawing. The peak pressure measured at each array declines with distance from the transition. Adjacent to the transition (Figure 11), pressure rises from the initiation of the experiment even at depths well below the frost line, due perhaps to the pressure exerted by the pipe close to its point of maximum curvature.

On the prefrozen side of the experiment (Figure 15), pressures decline at the two deepest sensors in response to the upward movement of the thaw front.

Glotzl cells

Figures 16 to 18 show results from the three Glotzl cell arrays, all of which are buried beneath the pipe. On the initially unfrozen side of the experiment (Figure 16), behaviour is broadly similar to that of the petur cell array closest to the transition. Results are more consistent with the Glotzl cells than with the Petur cells. On the prefrozen side (Figure 17) the cells show little change over the course of the experiment, since they were frozen into the soil before measurements were taken and have not experienced any thaw.

The Glotzl cell arrays in the unfrozen material and at the transition (Figure 18) both show a rapid increase in pressure with the onset of colder temperatures at day 215. Some cells in the array on the prefrozen side of the experiment appear to exhibit this behaviour as well. This may be due to temperature sensitivity in the cells, resulting from differences in the thermal expansion coefficients of oil within the cell and the steel of the cell walls.

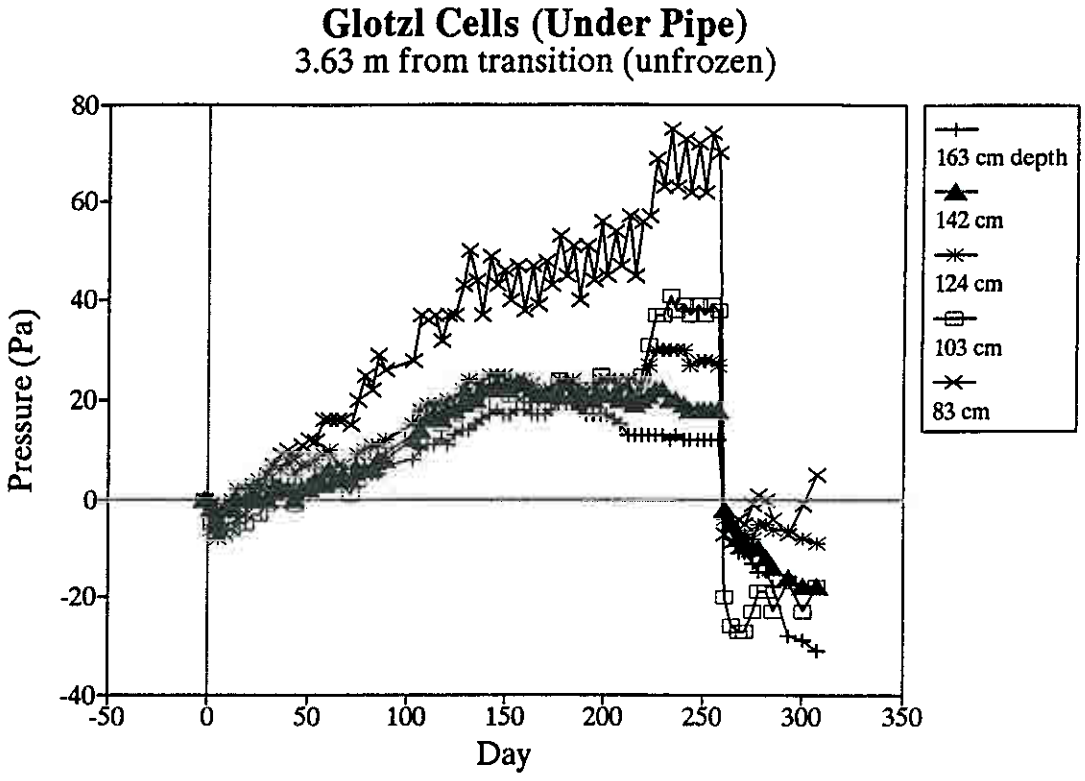


Figure 16

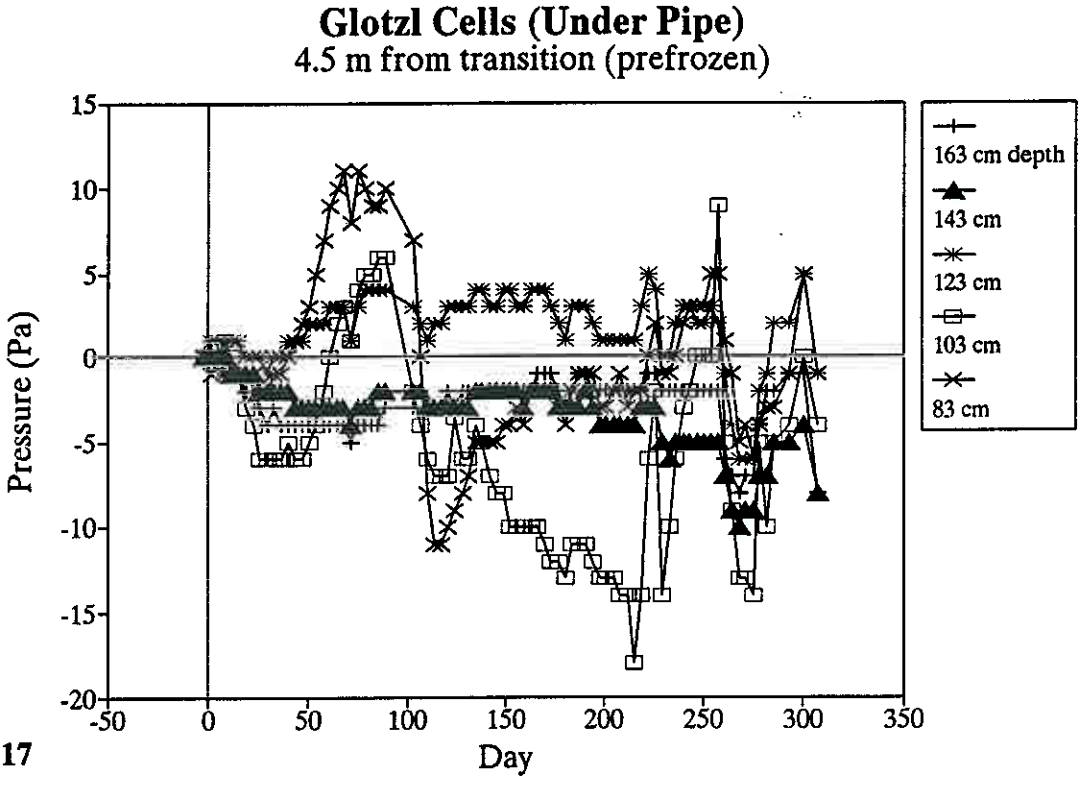


Figure 17

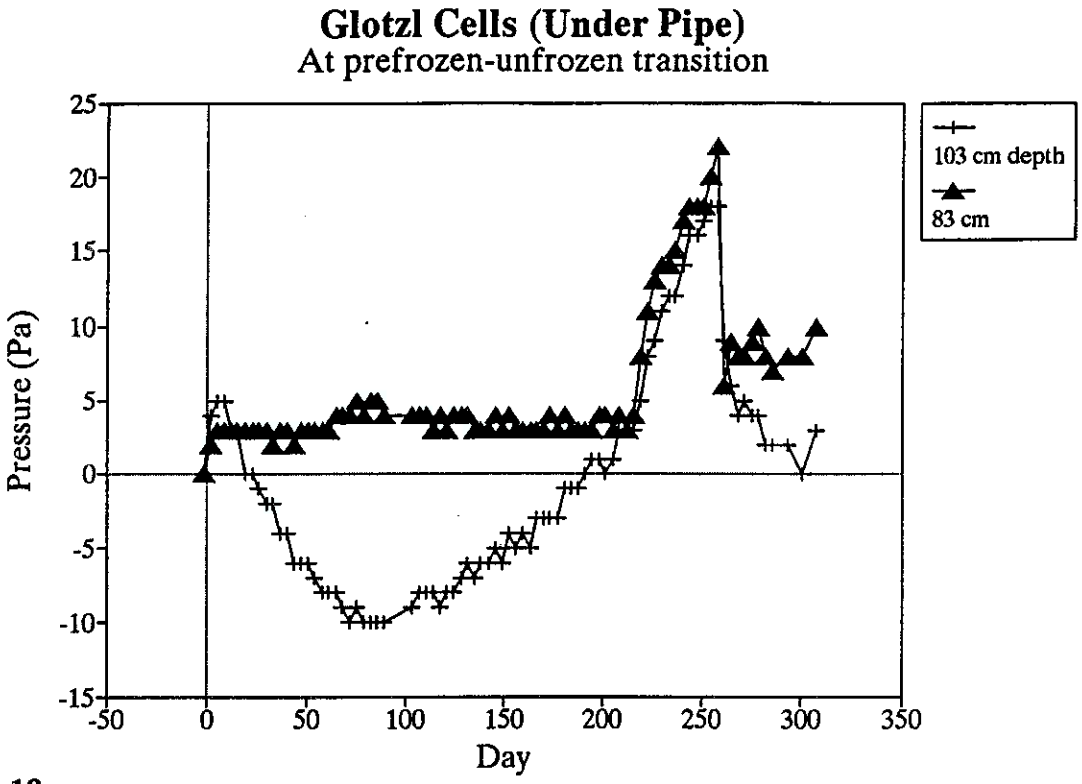


Figure 18

Soil movement and expansion

Optical survey

The soil surface is surveyed optically using a level mounted in the frame of the small door to the cold room. The reference point for all level measurements is an iron bar embedded in the concrete of a retaining wall just outside the facility. Survey points are laid out in a grid of nails embedded in the soil surface. There are 11 survey lines axial to the pipe, each having 30 marker nails at 50 cm spacing.

The soil surface was surveyed approximately monthly throughout the experiment. The configuration of the soil surface on selected survey dates is shown in Figures 19 to 23. The pattern of frost heave is not readily apparent from the raw survey data, due to the uneven initial surface and the frost heave which occurred on the prefrozen side during the period of freezing which preceded the start of the experiment. Manipulation of this data can reveal features of the spatial and temporal variation of the soil behaviour during the experiment. In this section, results for two simple manipulations of the surface heave data are presented:

- Total change in elevation from the start of freezing.
- The changing spatial distribution of the rate of heave and settlement over time.

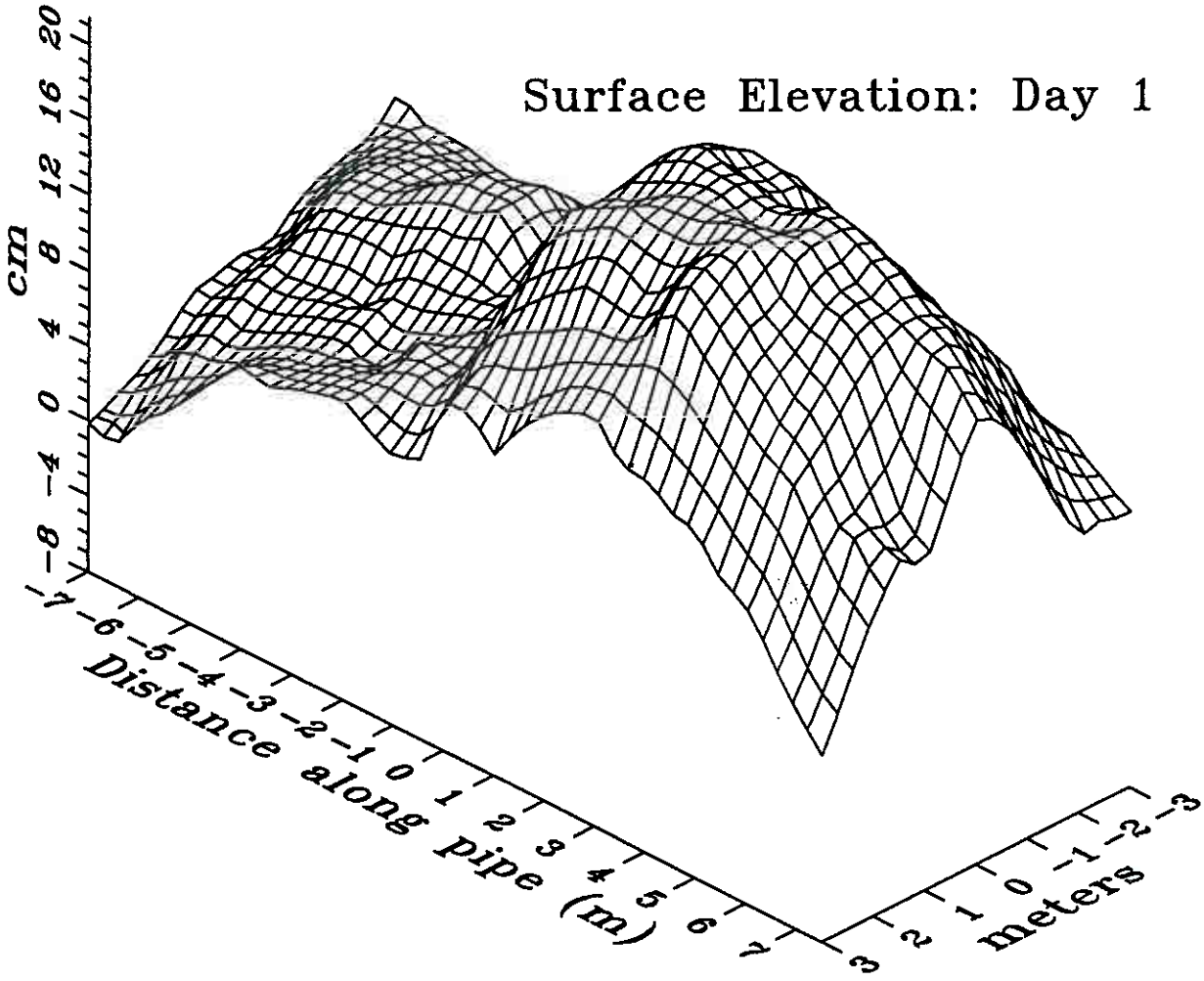

Surface Elevation: Day 1
cm
20
16
12
8
4
0
-4
-8
Distance along pipe (m)
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
meters
3 2 1 0 -1 -2 -3

Figure 19

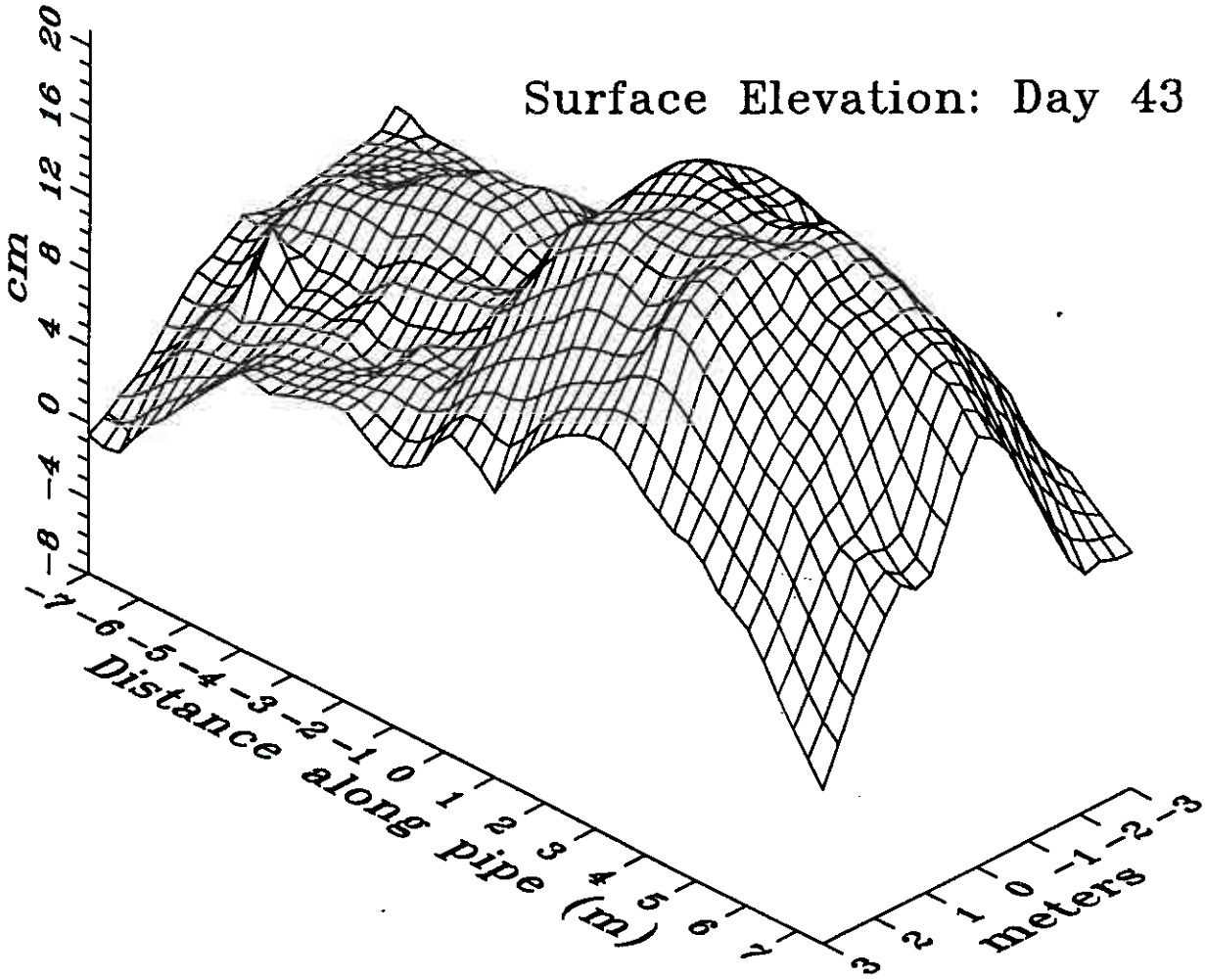

Surface Elevation: Day 43
cm
20
16
12
8
4
0
-4
-8
Distance along pipe (m)
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
meters
3
2
1
0
-1
-2
-3

Figure 20

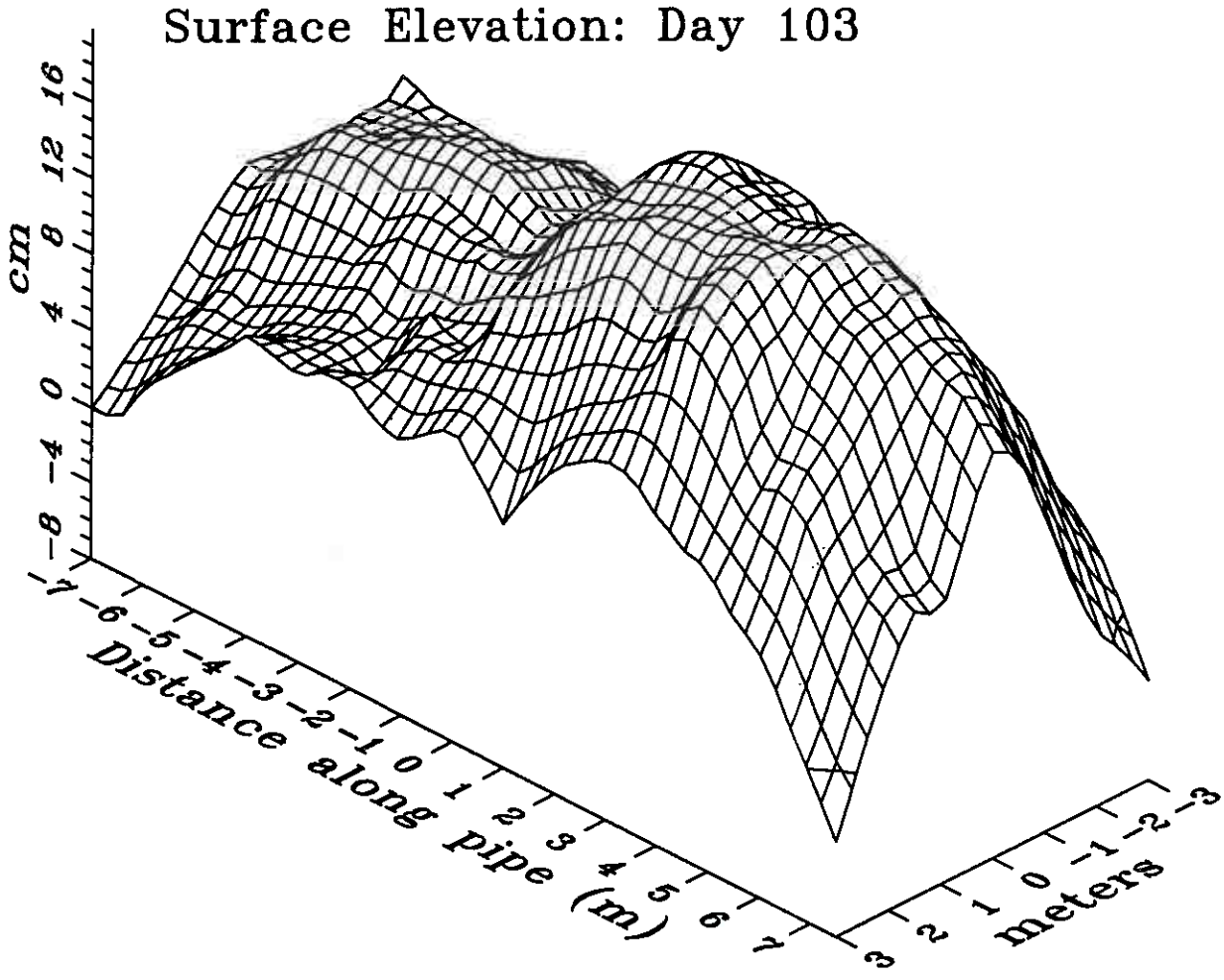

Surface Elevation: Day 103
cm
16
12
8
4
0
−4
−8
−7 −6 −5 −4 −3 −2 −1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 −1 −2 −3
meters

Figure 21

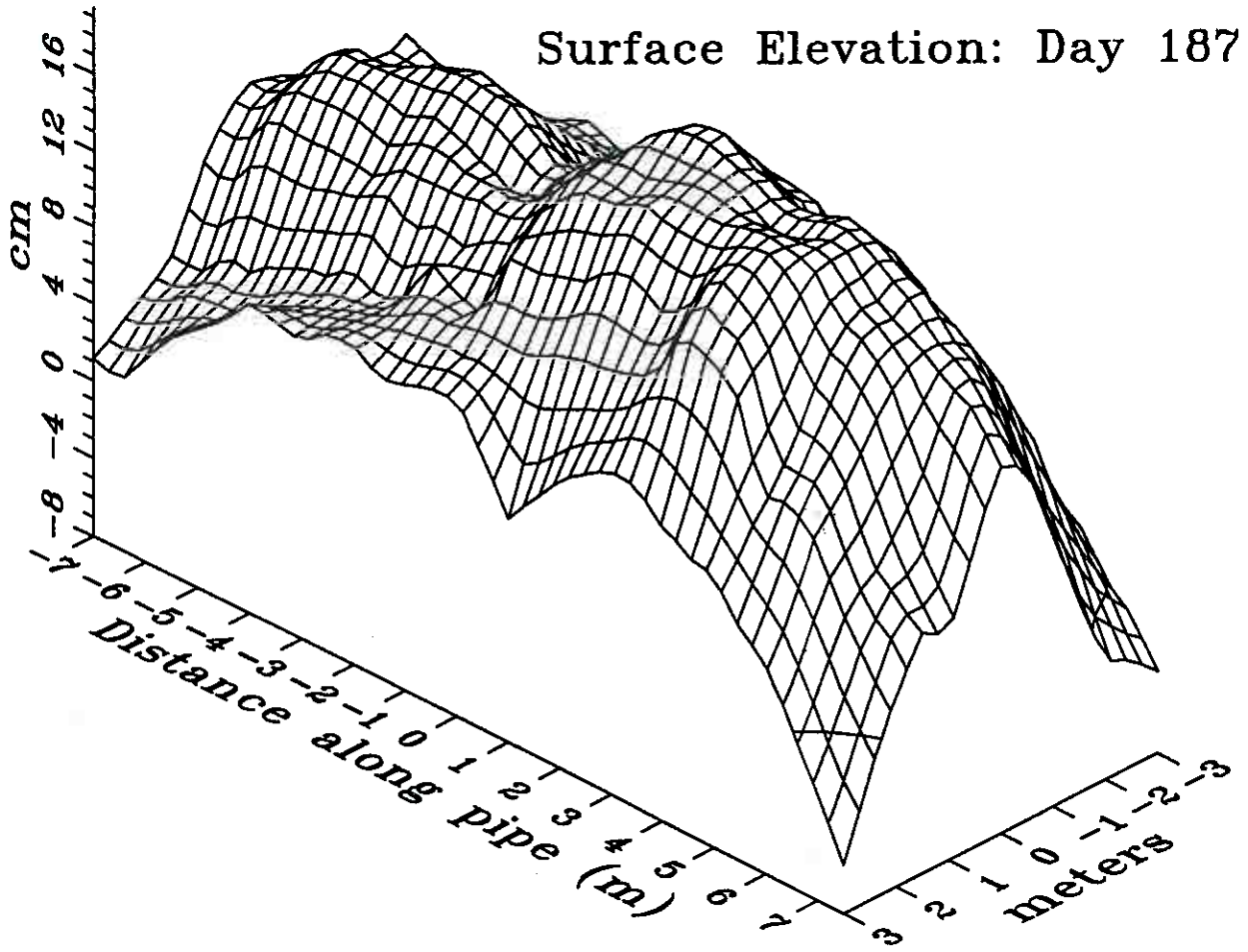

Surface Elevation: Day 187
cm
16
12
8
4
0
−4
−8
−7 −6 −5 −4 −3 −2 −1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 −1 −2 −3
meters

Figure 22

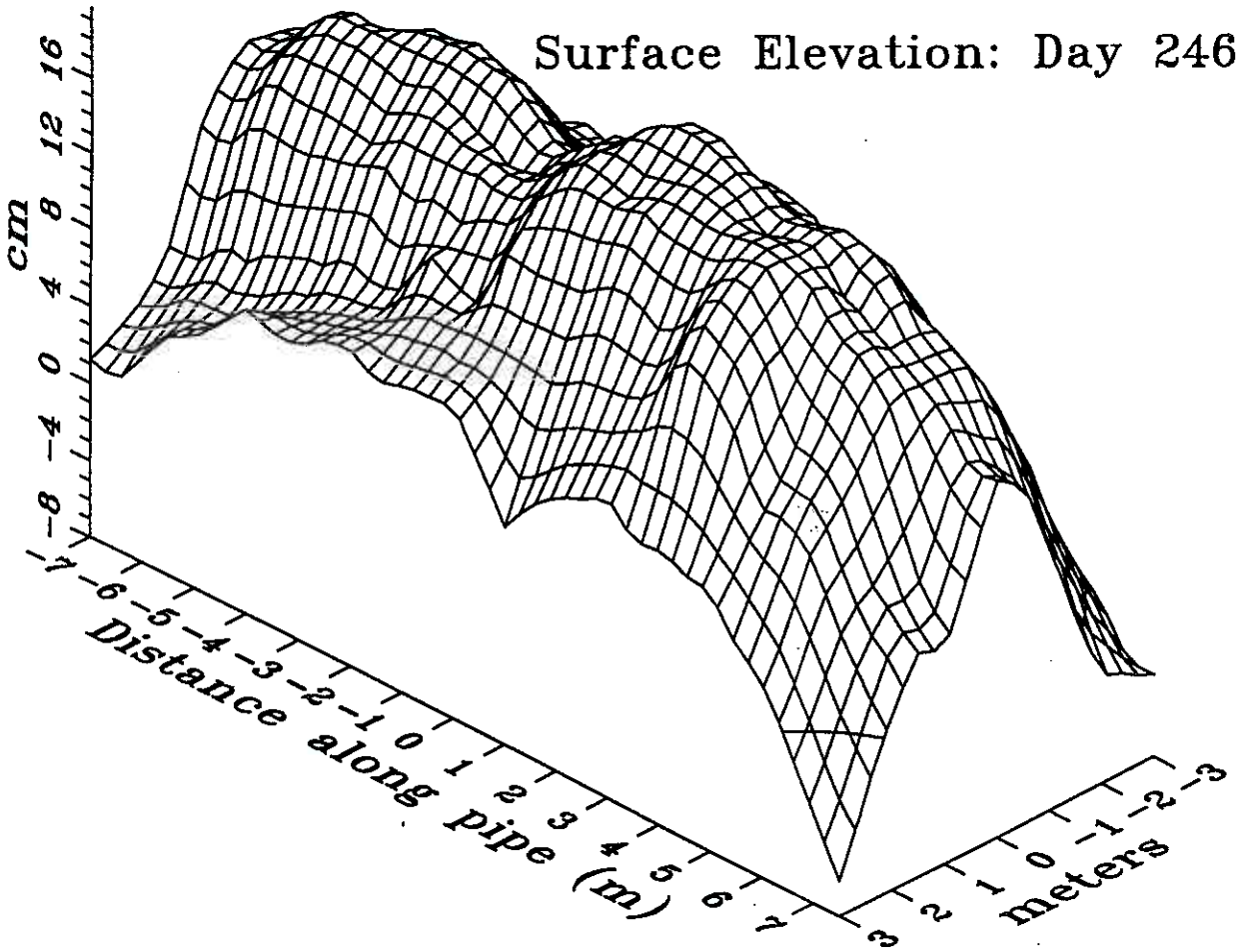

Surface Elevation: Day 246
cm
-8 -4 0 4 8 12 16
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 -1 -2 -3
meters

Figure 23

Elevation change

The change in elevation of the soil surface was extracted from the surface survey data (Figures 24-34), by examining the change in elevation from the start of the experiment. The dominant features of the series are:

- Settlement begins almost immediately and continues throughout the experiment on the prefrozen side.
- Heave is greater adjacent to the pipe than directly beneath it for some distance from the transition.
- Frost heave of the pipe increases with distance from the interface, despite the reduced frost penetration away from the transition.
- Frost heave is augmented along the frozen transition away from the pipe, due to deeper frost penetration close to the prefrozen material.

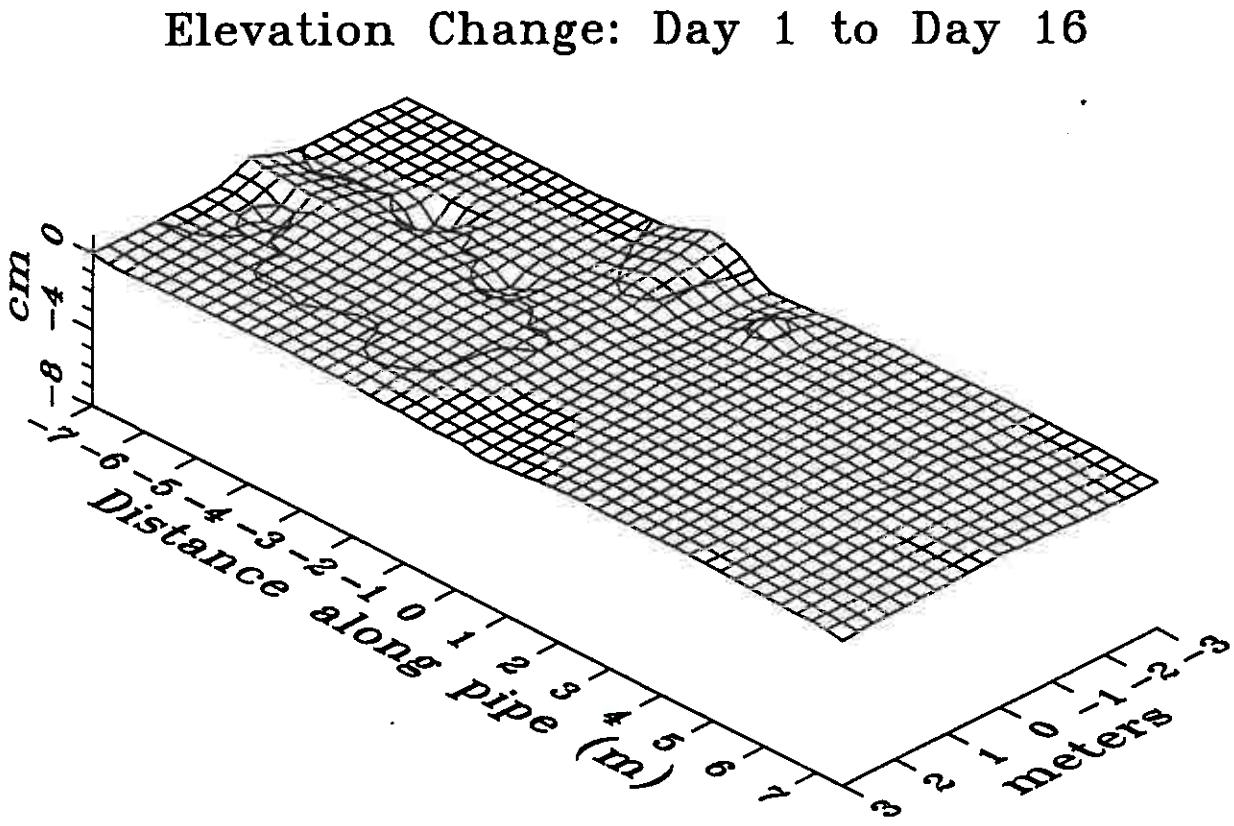

Elevation Change: Day 1 to Day 16
cm
0
-4
-8
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 -1 -2 -3
meters

Figure 24

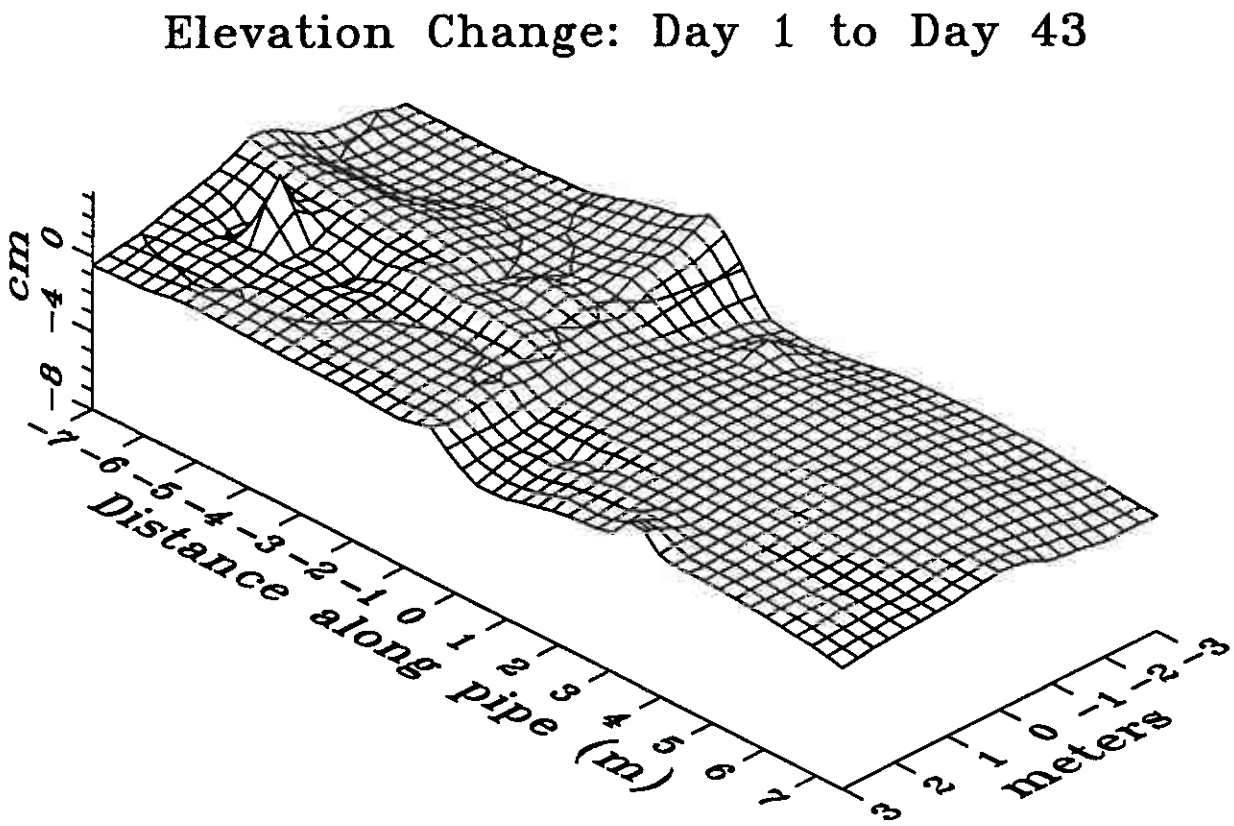

Elevation Change: Day 1 to Day 43
cm
0
-4
-8
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 -1 -2 -3
meters

Figure 25

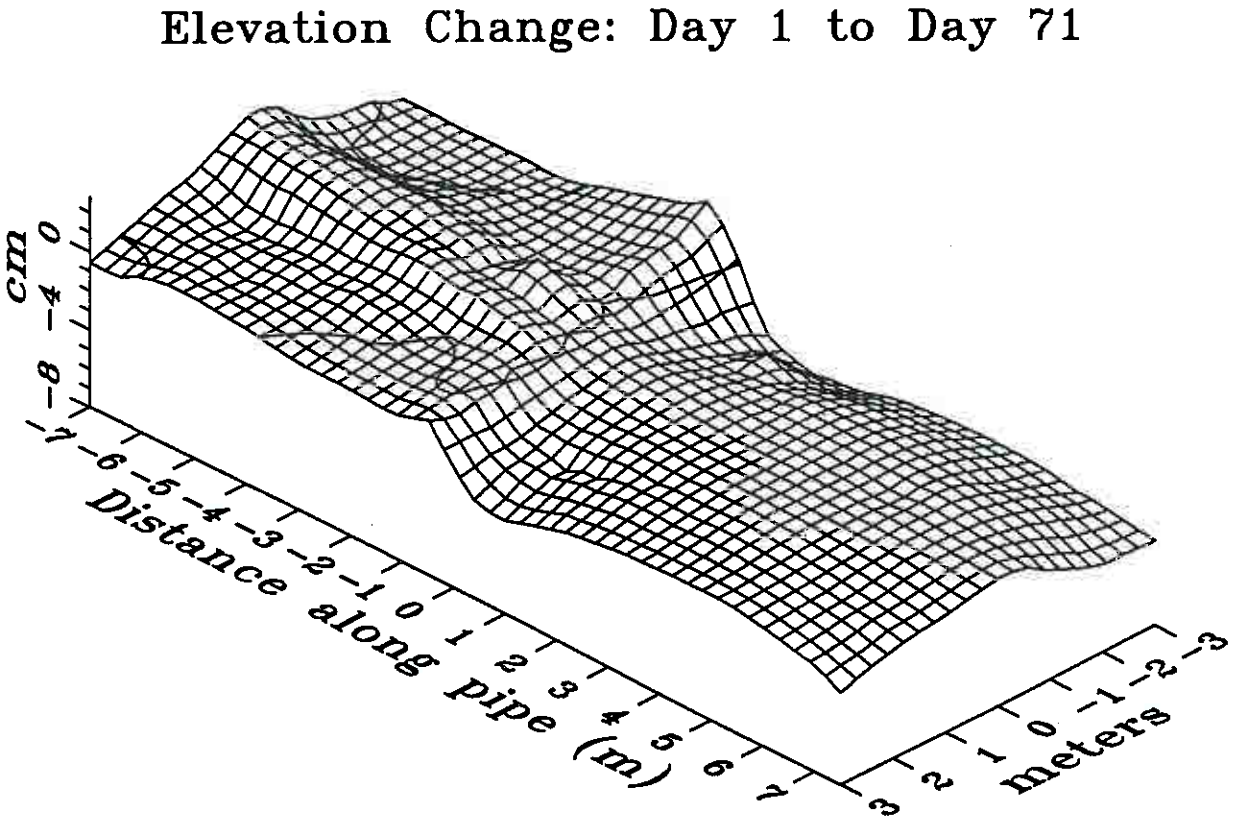

Elevation Change: Day 1 to Day 71
cm
0
-4
-8
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 -1 -2 -3
meters

Figure 26

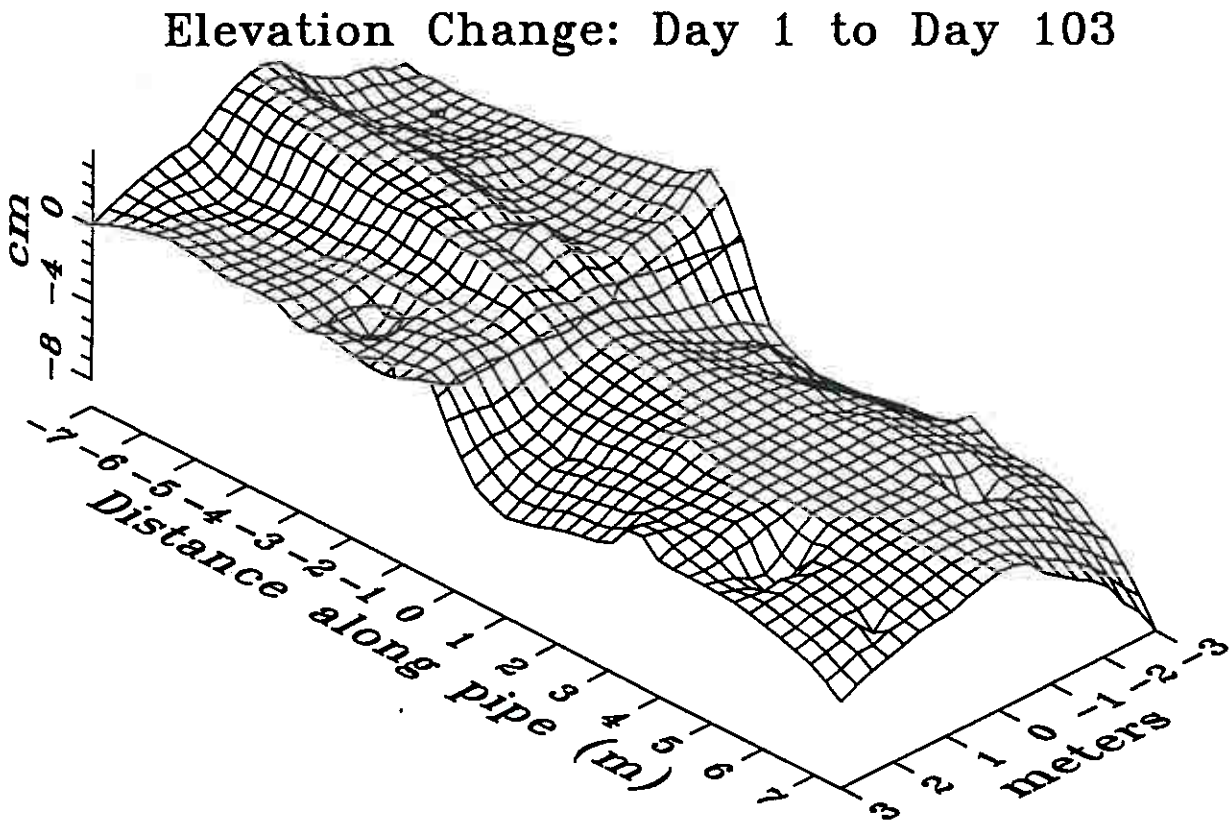

Elevation Change: Day 1 to Day 103
cm
0
-4
-8
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 -1 -2 -3
meters

Figure 27

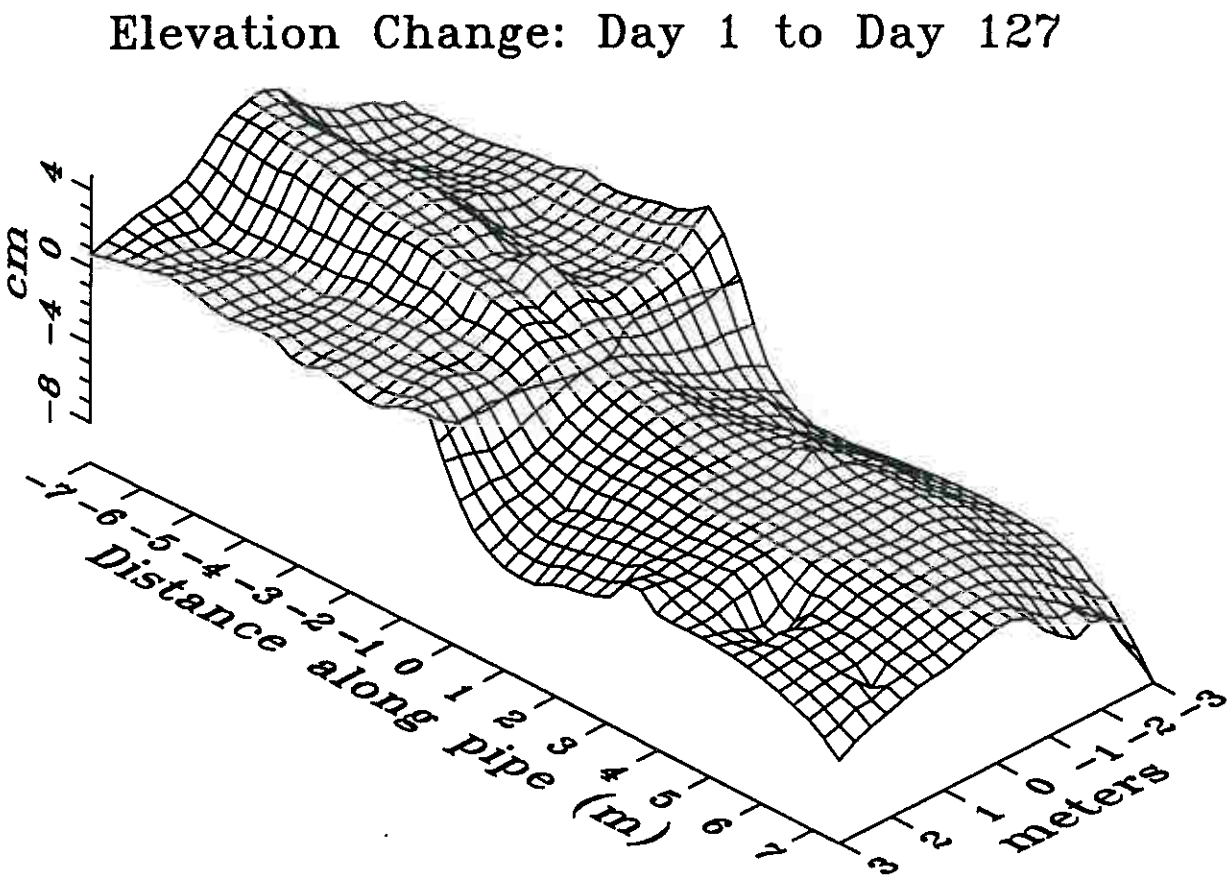

Elevation Change: Day 1 to Day 127
cm
4
0
-4
-8
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 -1 -2 -3
meters

Figure 28

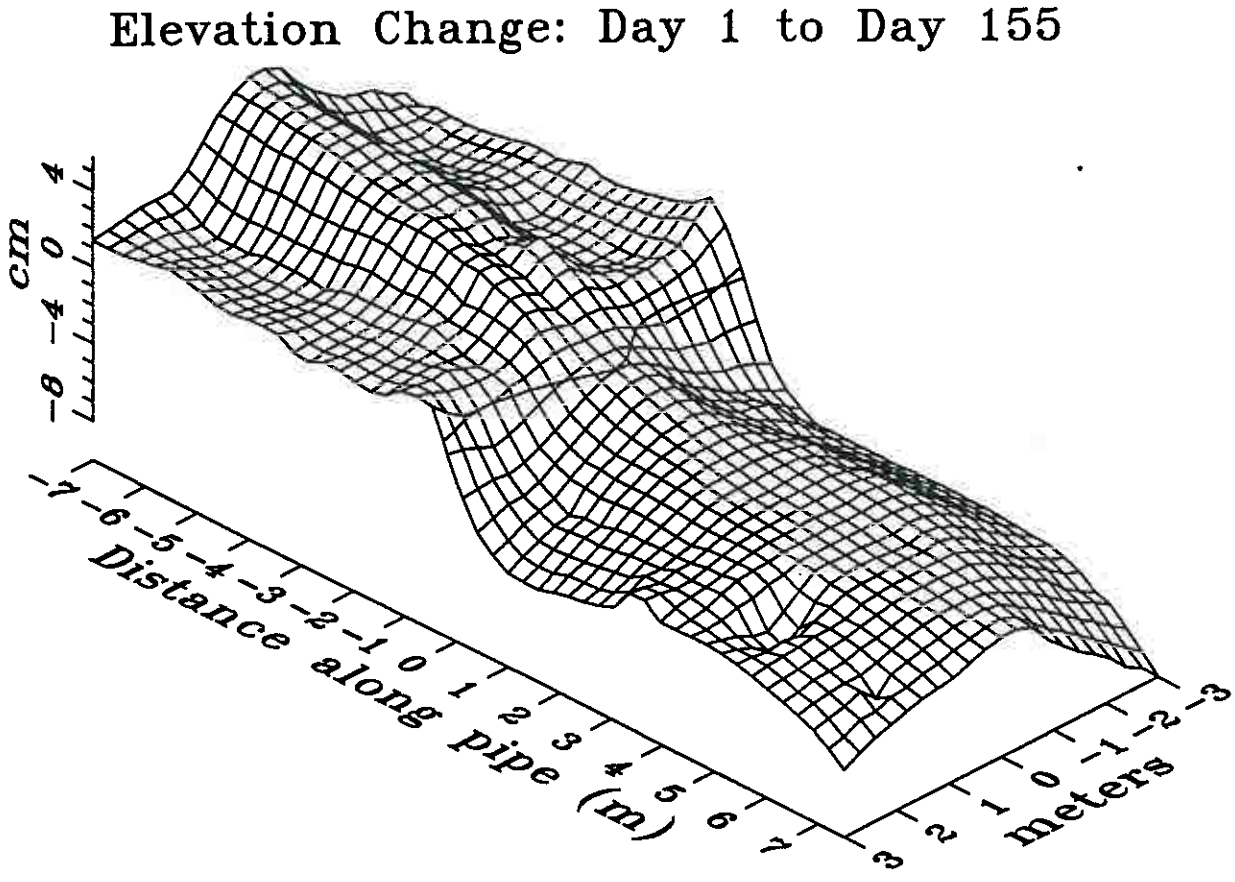

Elevation Change: Day 1 to Day 155
cm
-8 -4 0 4
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 -1 -2 -3
meters

Figure 29

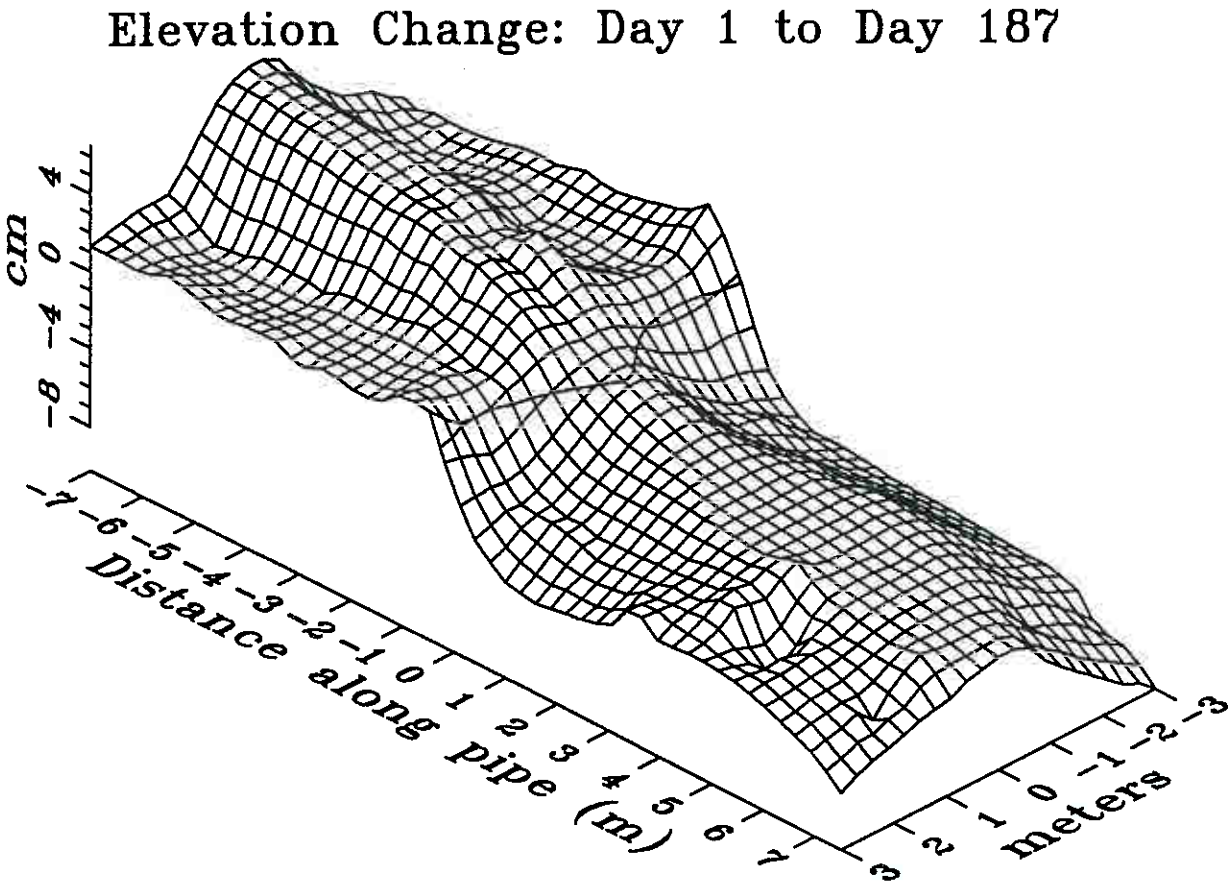

Elevation Change: Day 1 to Day 187
cm
-8 -4 0 4
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 -1 -2 -3
meters

Figure 30

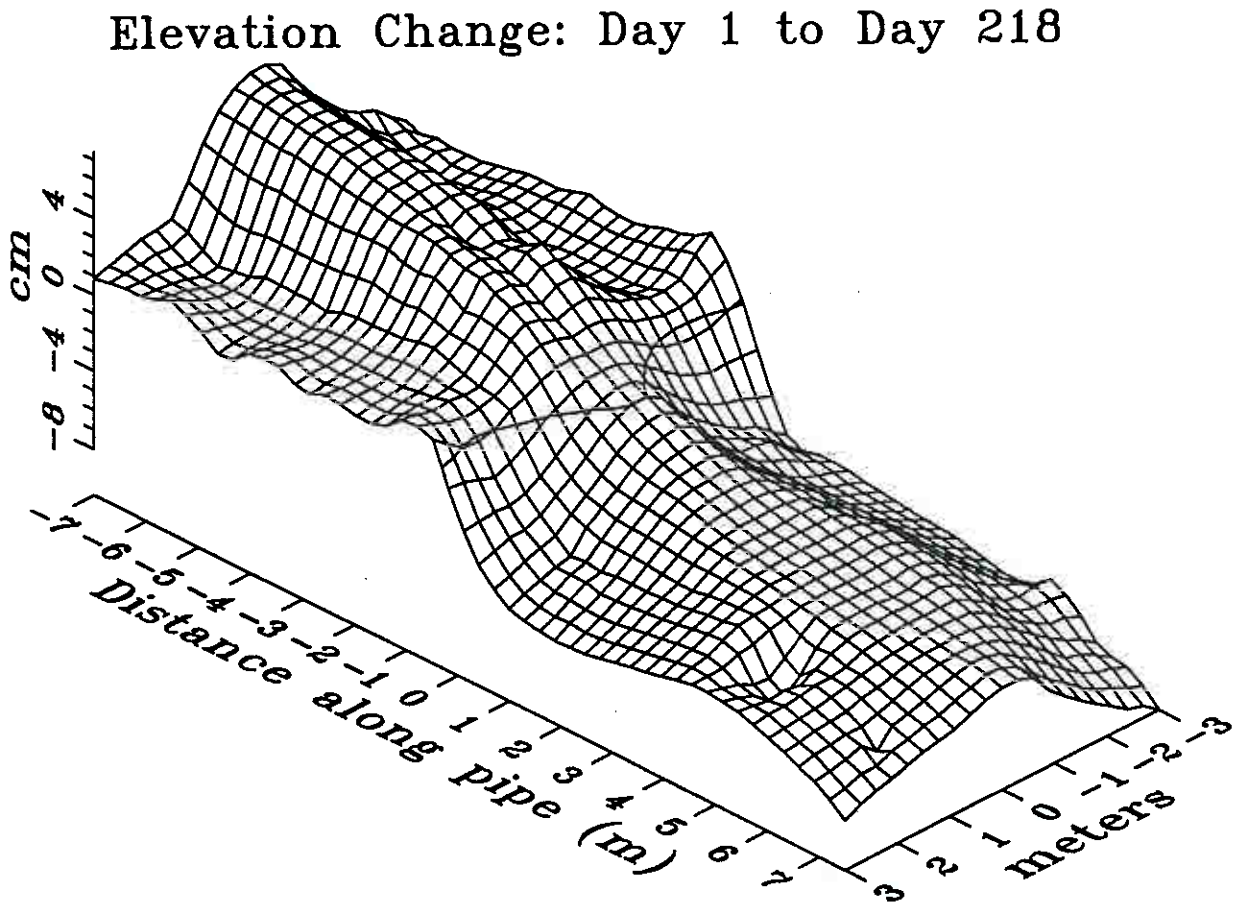

Elevation Change: Day 1 to Day 218
cm
4
0
-4
-8
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 -1 -2 -3
meters

Figure 31

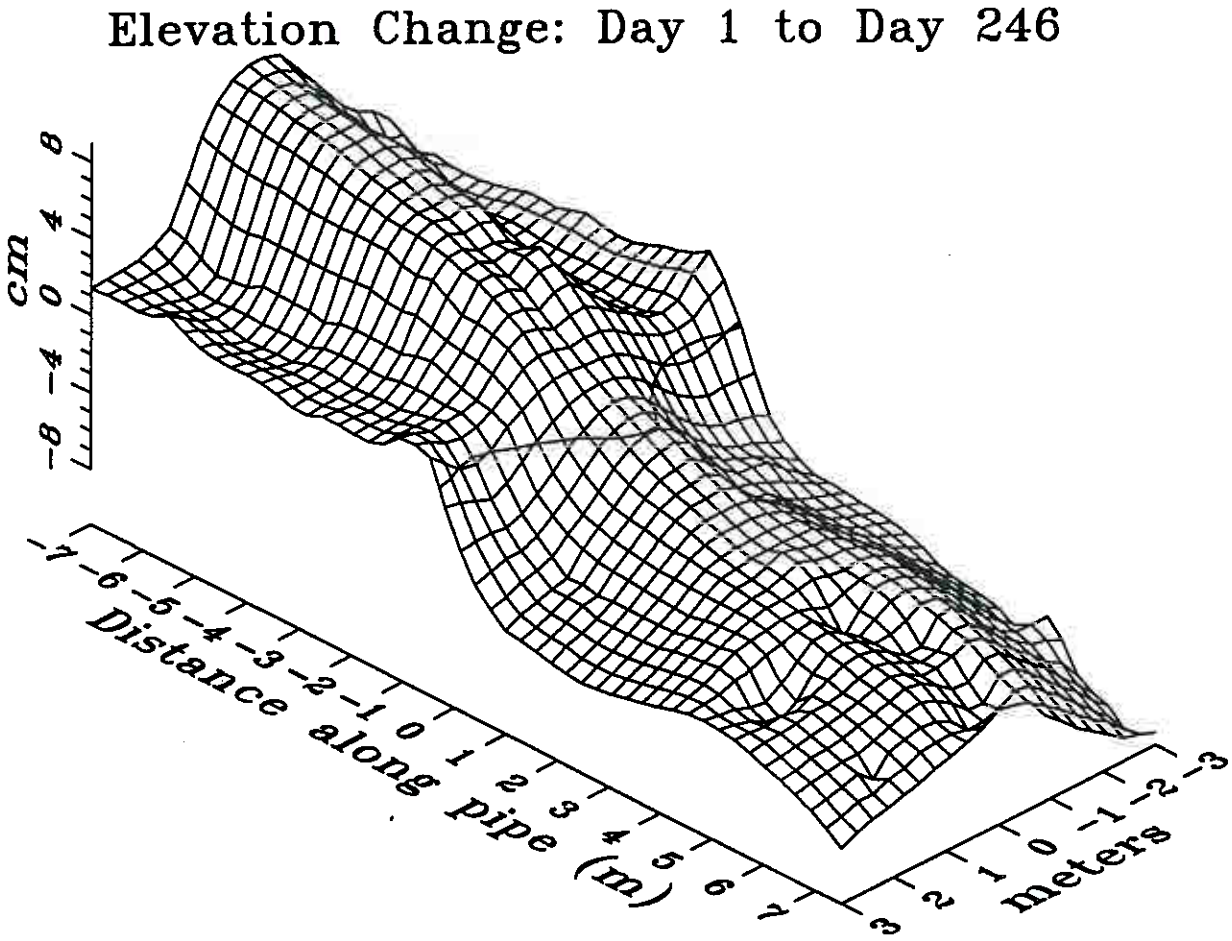

Elevation Change: Day 1 to Day 246
cm
8
4
0
-4
-8
Distance along pipe (m)
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
meters
3 2 1 0 -1 -2 -3

Figure 32

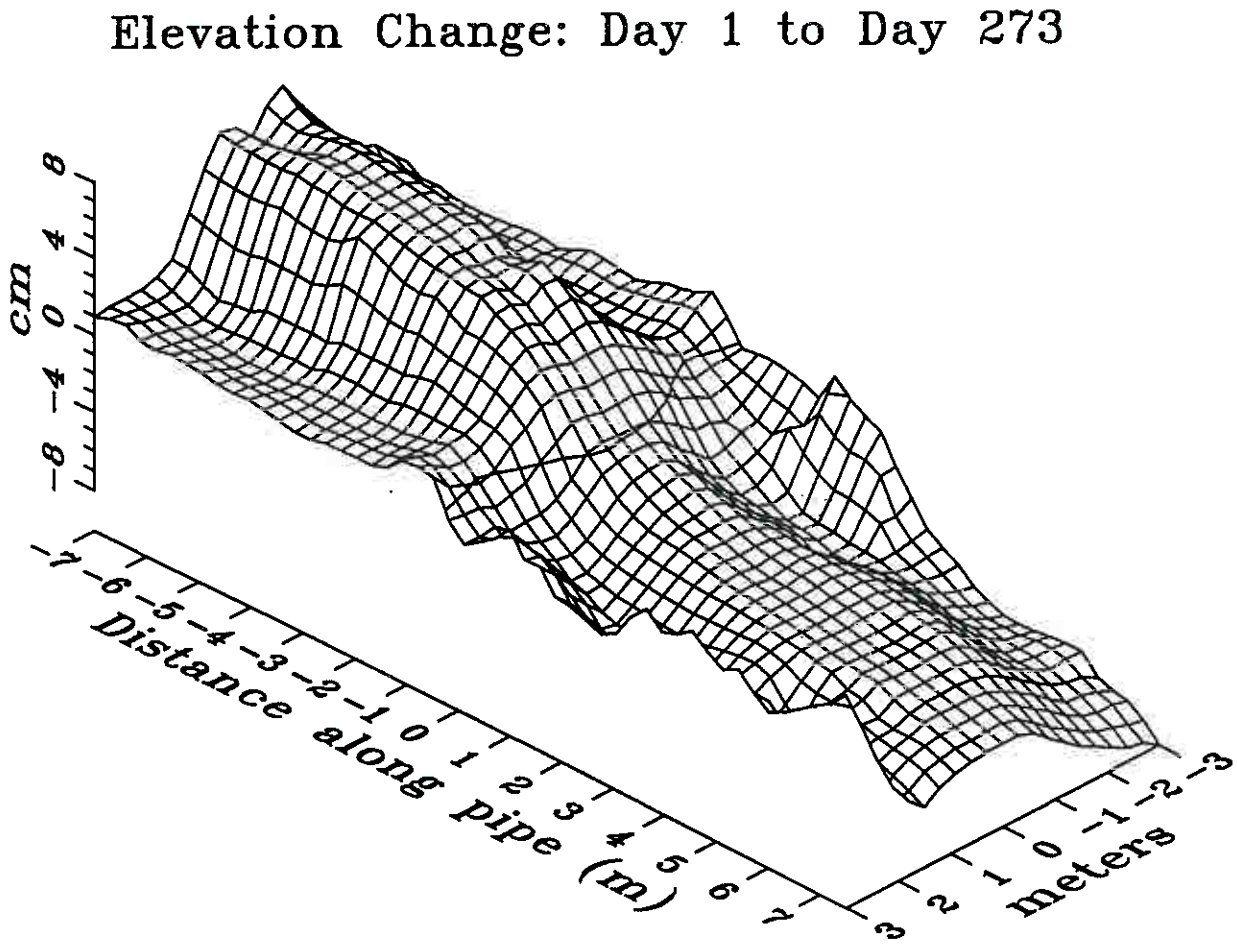

Elevation Change: Day 1 to Day 273
cm
8
4
0
-4
-8
Distance along pipe (m)
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
meters
3 2 1 0 -1 -2 -3

Figure 33

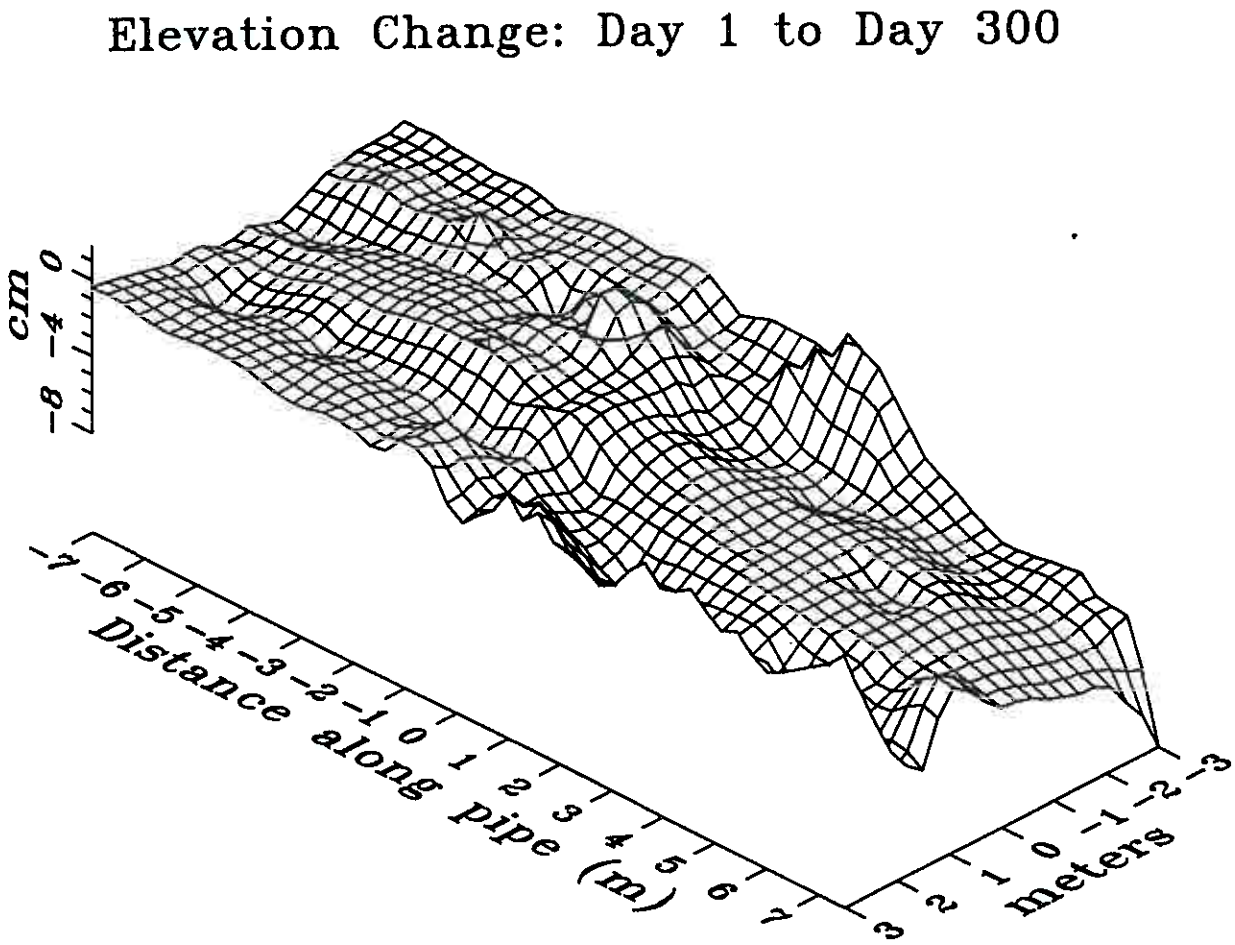

Elevation Change: Day 1 to Day 300
cm
0
-4
-8
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 -1 -2 -3
meters

Figure 34

Heave and settlement rates over time

The changing spatial distribution of the rate of elevation change over time was calculated by examining elevation changes between dates within the survey record. Figures 35 to 43 show the spatial variation in heave/settlement rate calculated for different periods of the freeze. In these figures, the relatively subtle variations in the calculated rates of elevation change amplify minor errors in the original survey data. These errors are apparent as localized peaks and hollows, and it is assumed that these can be ignored.

Rates are not calculated after the initiation of thaw, due to the obstruction presented by the insulating wall.

The dominant features are:

- The rate of heave is highest adjacent to the pipe in the initially unfrozen section, while thaw settlement is distributed relatively uniformly over the prefrozen section, although it is less near the pipe.
- Both heave and settlement rates generally decrease as the freeze cycle progresses.
- In the initial stages, the heave rate is high in the unfrozen material at the transition, reflecting the higher frost penetration rate. Adjacent to this on the prefrozen side, there is a slightly greater settlement rate adjacent to the transition. More rapid thawing at the base and consolidation of the silt as a result of water being drawn toward the freezing material on the heaving side of the transition may also contribute to this.
- The depression immediately above the pipe axis near the transition develops predominantly between days 16 and 43, though its development spans days 1 to 71. This suggests that it is due to frost heaving in the soil beside the pipe rather than uplift resistance.

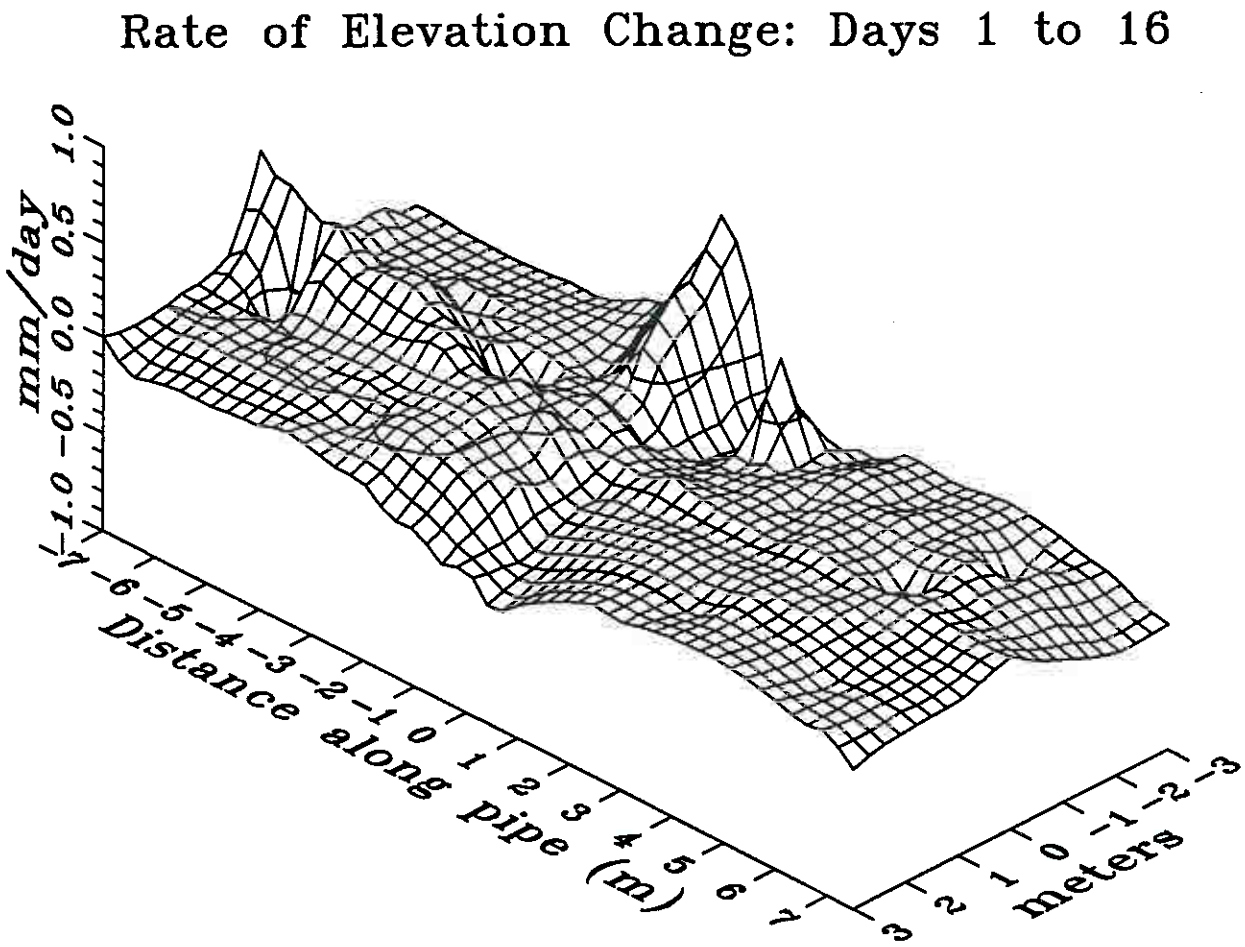

Rate of Elevation Change: Days 1 to 16
mm/day
-1.0 -0.5 0.0 0.5 1.0
Distance along pipe (m)
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
meters
3 2 1 0 -1 -2 -3

Figure 35

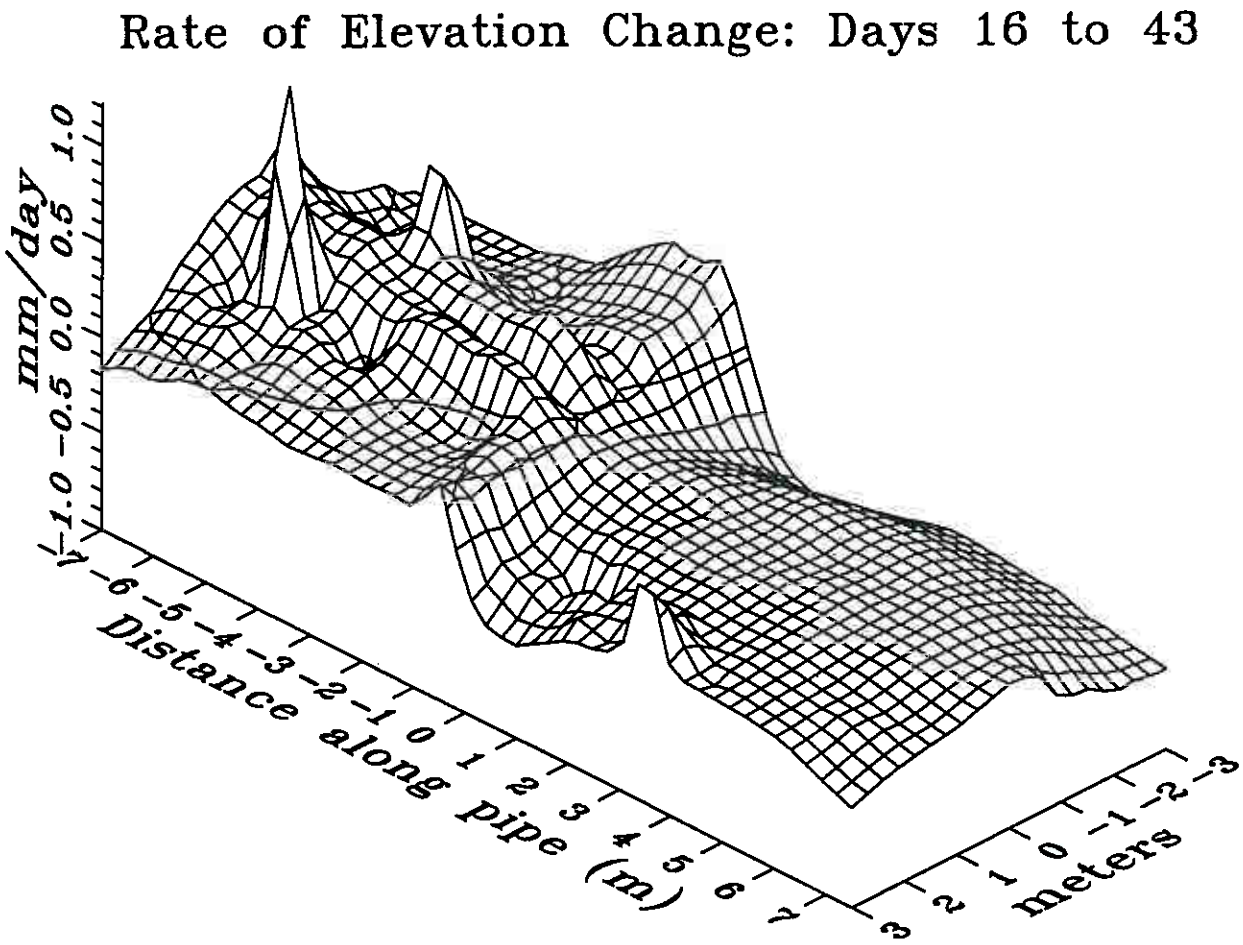

Rate of Elevation Change: Days 16 to 43
mm/day
-1.0 -0.5 0.0 0.5 1.0
Distance along pipe (m)
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
meters
3 2 1 0 -1 -2 -3

Figure 36

Rate of Elevation Change: Days 43 to 71

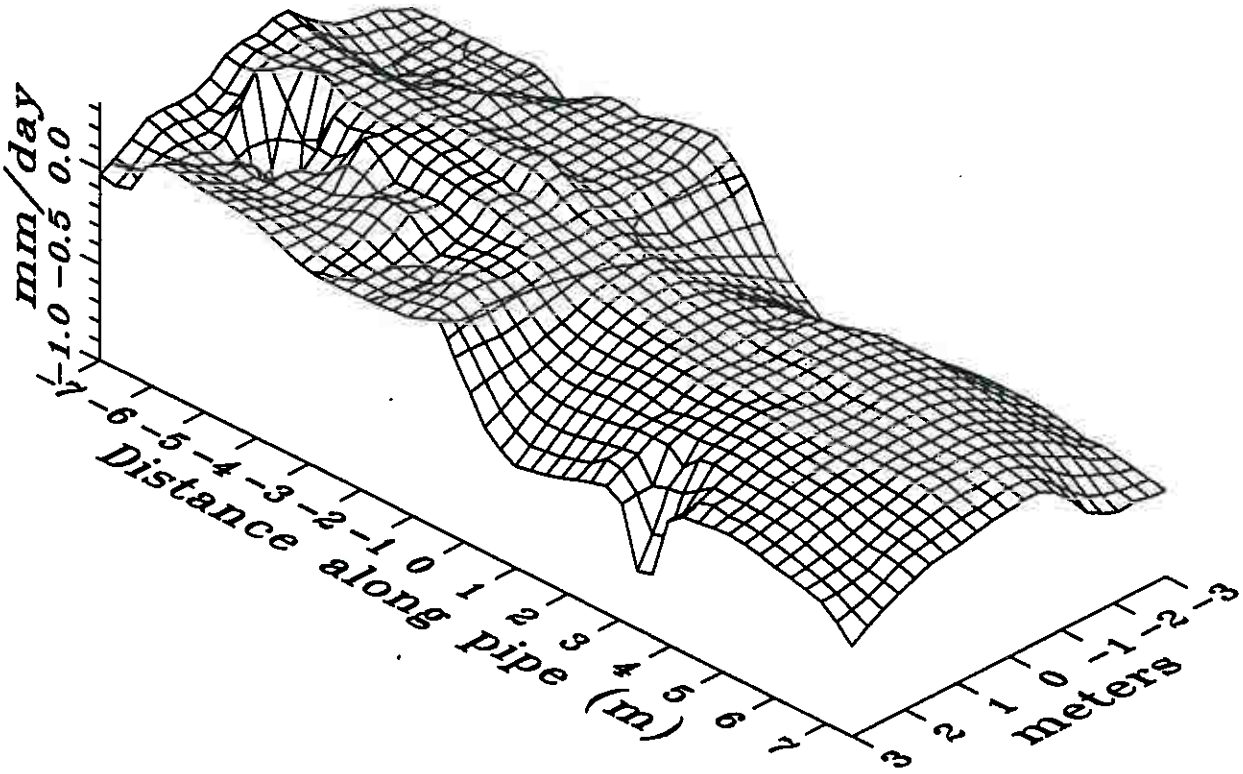


Figure 37

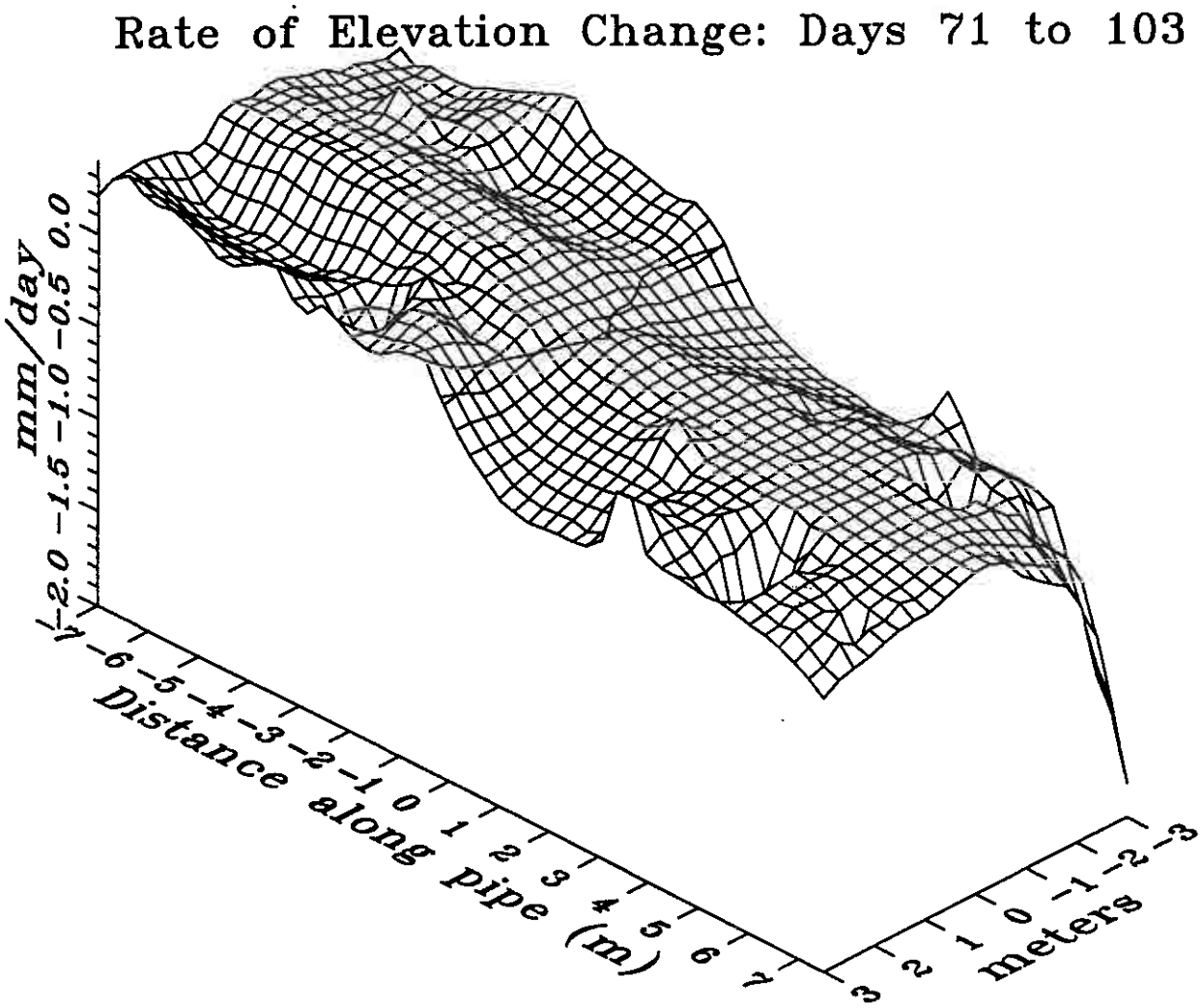

Rate of Elevation Change: Days 71 to 103
mm/day
-2.0 -1.5 -1.0 -0.5 0.0
Distance along pipe (m)
-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
meters
3 2 1 0 -1 -2 -3

Figure 38

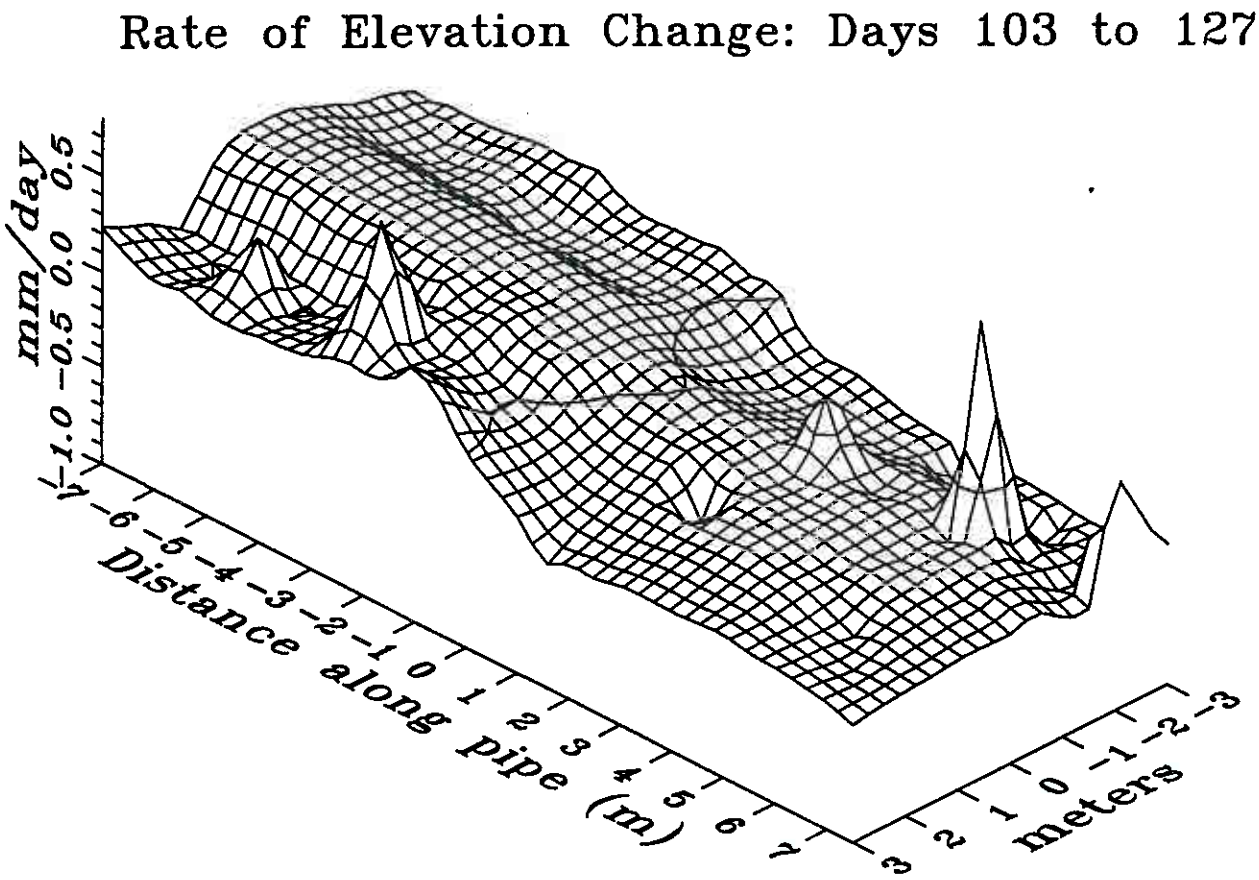

Rate of Elevation Change: Days 103 to 127
mm/day
-1.0 -0.5 0.0 0.5
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 -1 -2 -3
meters

Figure 39

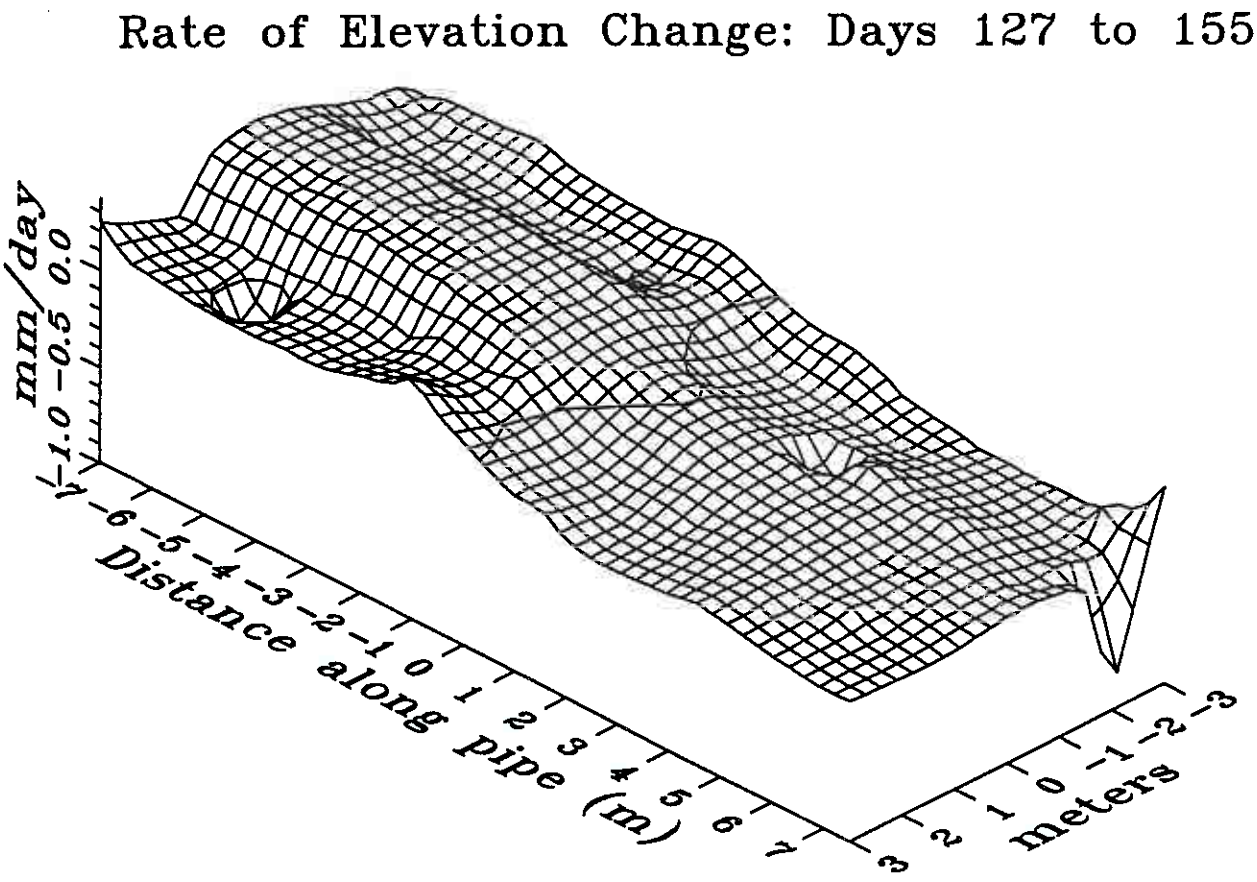

Rate of Elevation Change: Days 127 to 155
mm/day
-1.0 -0.5 0.0
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 -1 -2 -3
meters

Figure 40

Rate of Elevation Change: Days 155 to 187

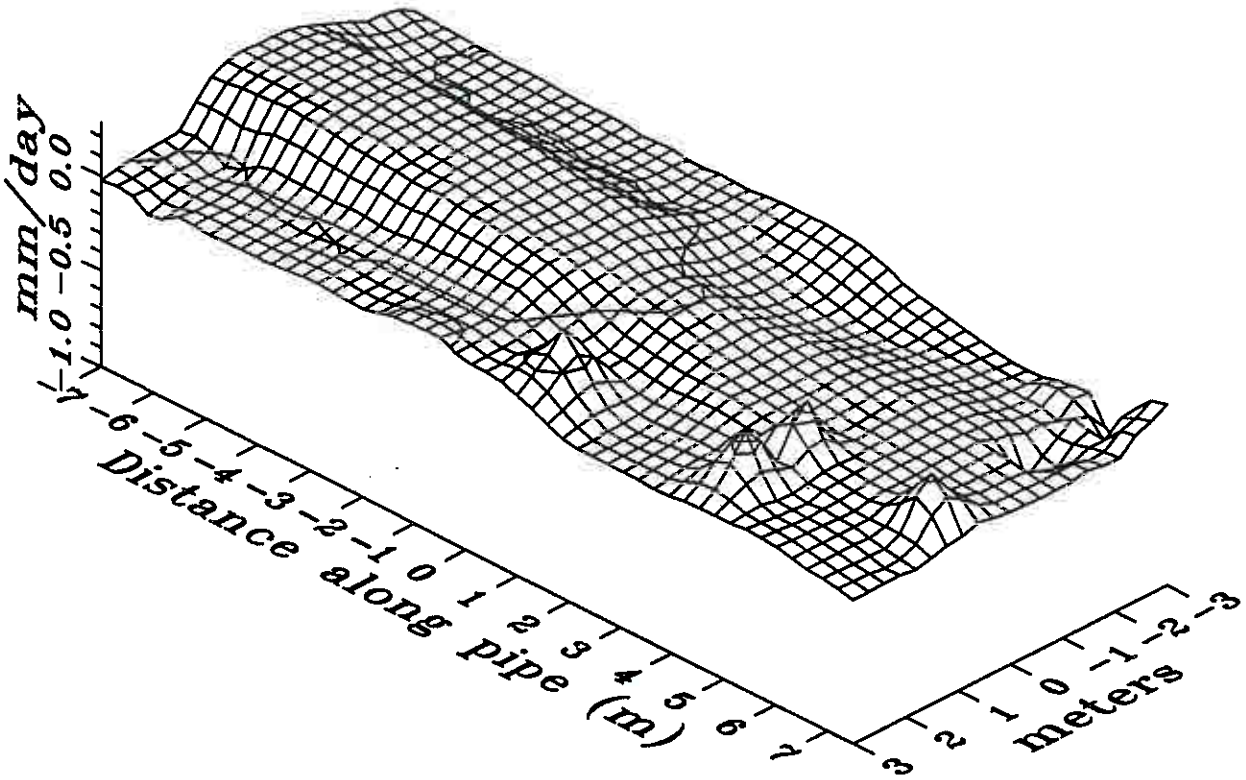


Figure 41

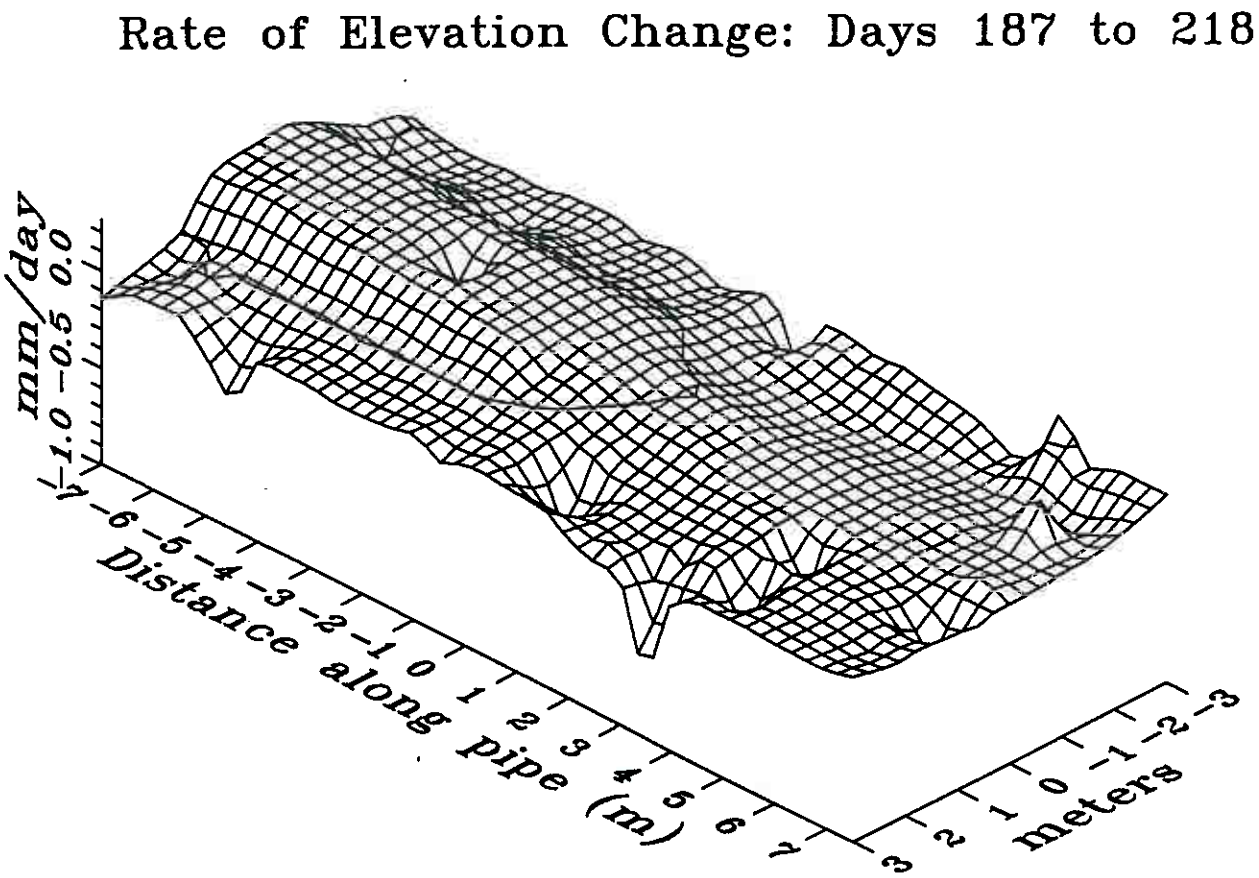

Rate of Elevation Change: Days 187 to 218
mm/day
-1.0 -0.5 0.0
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
Distance along pipe (m)
3 2 1 0 -1 -2 -3
meters

Figure 42

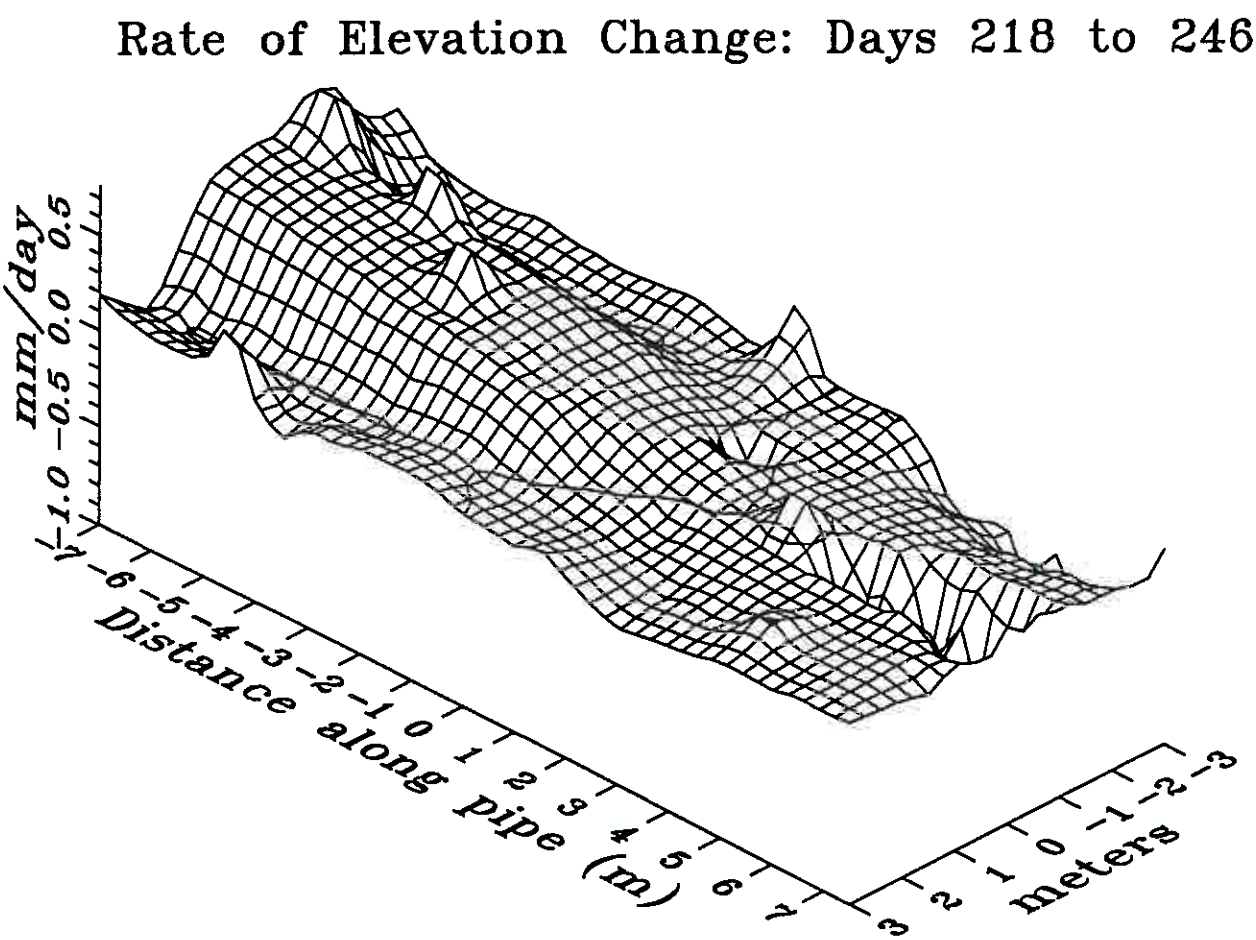

Rate of Elevation Change: Days 218 to 246
mm/day
-1.0 -0.5 0.0 0.5
Distance along pipe (m)
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
meters
3 2 1 0 -1 -2 -3

Figure 43

Magnet ring system
Measurements using the magnet soil strain system were not started until day 150 of the freeze due to problems with the measurement apparatus. The device was out of operation for two other extended periods, thereby limiting the utility of the measurements made with this system during the first freeze cycle.

Bison cells

Bison soil strain gauges (Bison "cells") consist of resin covered discs containing induction coils. The cells are buried co-axially, at spacings of 1 to 4 times their diameter. The measurement device sends a sinusoidal signal through one cell, which is received by a second cell. The ratio of emitted to received amplitudes is calibrated to cell spacing. A series of cells arranged in an array permits monitoring of soil strain over several depths: cells are used alternately as emitters and receivers as measurements are taken.

Results from two Bison cell arrays 2 m away from the pipe on the initially unfrozen side of the experiment are shown in Figures 44 and 45. Frost did not penetrate to the depth of the upper Bison cell at either site. Overall, movements between cells in these arrays was limited to 1-2 mm over the course of the experiment. Both sites show that some consolidation took place in the zone between 60 and 80 cm depth (just below the level of the pipe), presumably due to water movement to the freezing front around the pipe.

Results for the Bison cell sites on the prefrozen side of the experiment are shown in Figures 46 and 47. Ongoing thaw settlement from the base of the prefrozen material is apparent until pipe temperatures are reduced, after which a modest amount of frost heave is apparent in the layer containing the freezing front (63-81 cm layer).

Results from two Bison cell arrays beneath the pipe on the initially unfrozen side of the experiment are shown in Figures 48 and 49. At these sites, the upper cell is attached to the pipe, so that the strain in this layer will include any gap which develops between the pipe and the soil.

Behaviour of the zone between the pipe and the 79.5 cm depth (about 20 cm thick) is similar at the two sites, showing a period of rapid initial expansion (about 50 days 2.4 m from the transition, and about 70 days 3.25 m from the transition), after which there is little further expansion until the lowering of pipe temperatures. The 2 to 3 mm expansion in the uppermost layer following the lowering of pipe temperatures suggests the presence of a gap between the base of the pipe and the soil which is increased by arching of the pipe, since lower temperatures are unlikely to produce increased frost heave in this layer. During the thaw relaxation period, the cell spacing in this layer quickly becomes less than at the start of the experiment, due to consolidation and lateral displacement of the thawing soil.

One difference between the two sites is the consolidation in the zone below the freezing front: consolidation of the 97.5-115.5 cm layer is much greater at the site closer to the transition. This may be due to the downward pressure exerted by the pipe in the zone closer to

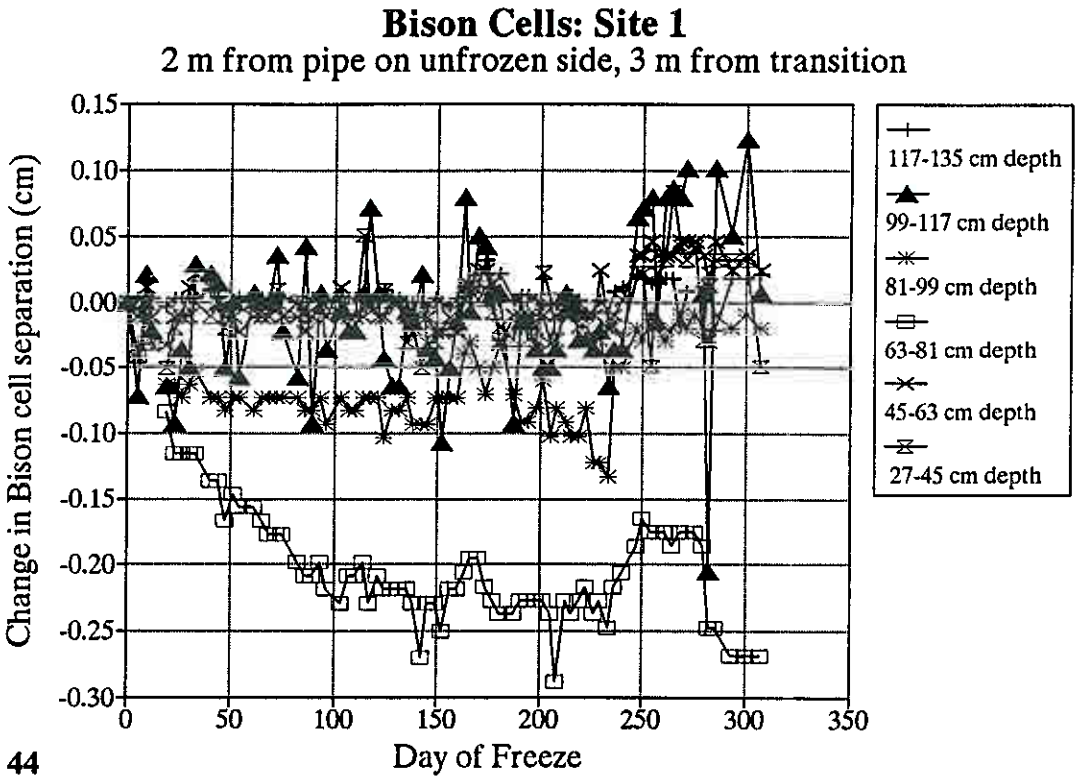


Figure 44

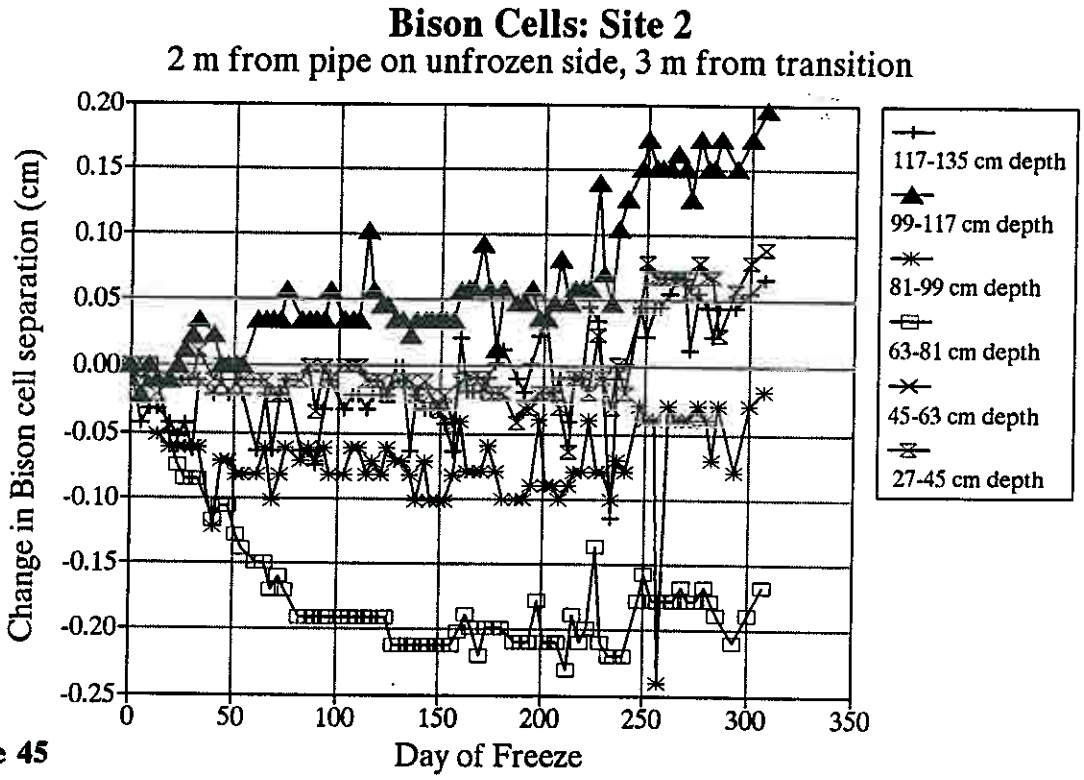


Figure 45

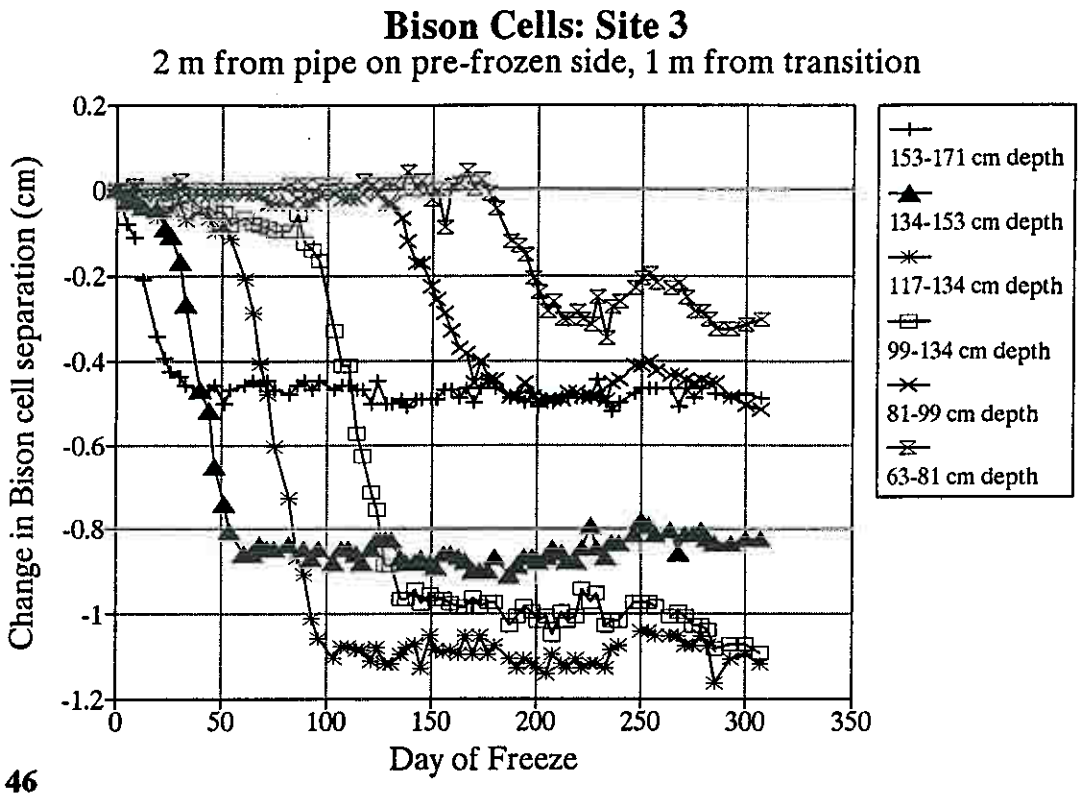


Figure 46

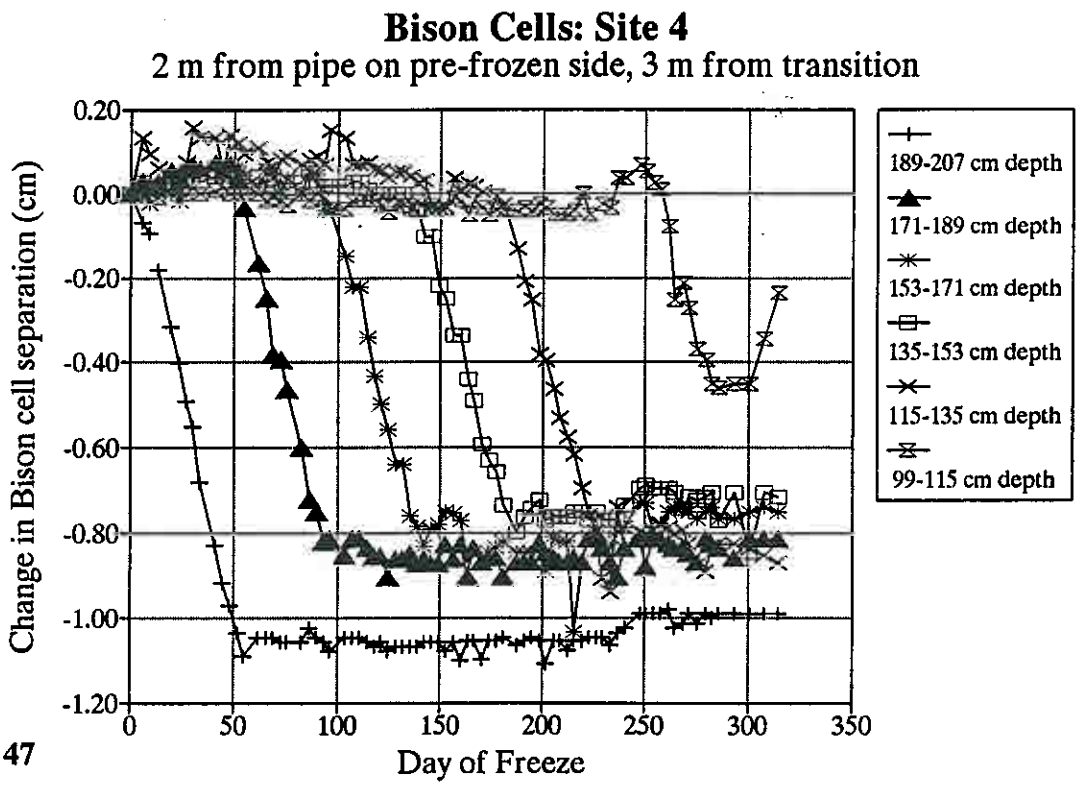


Figure 47

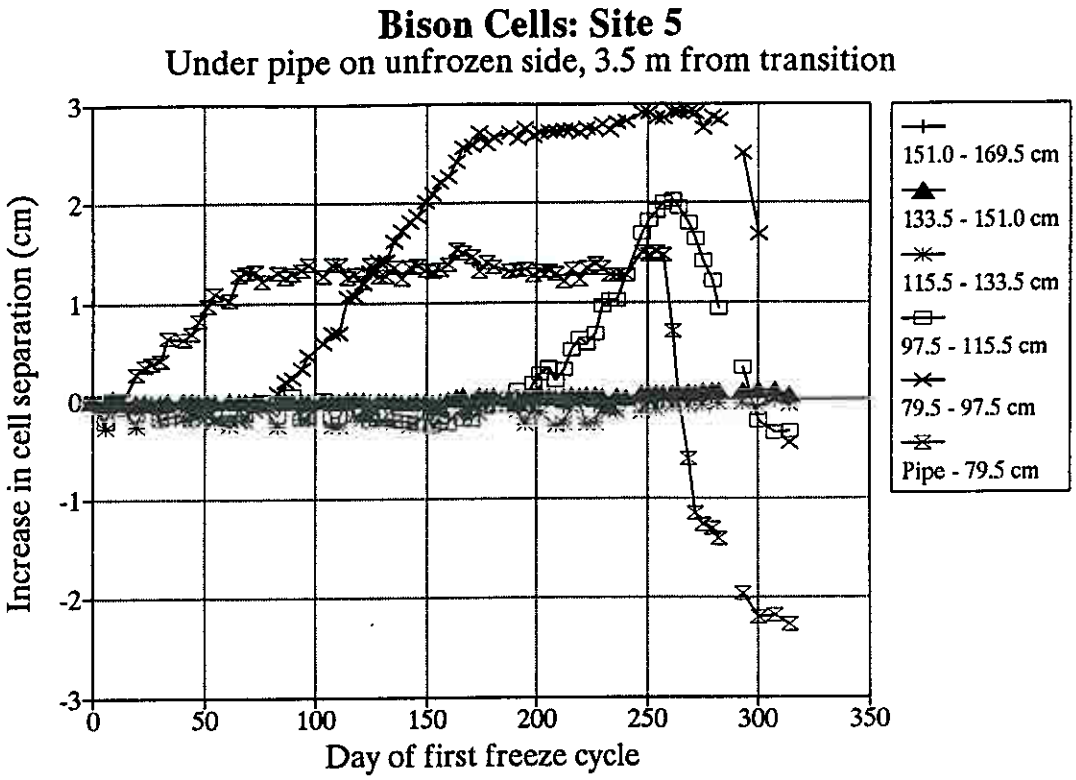


Figure 48

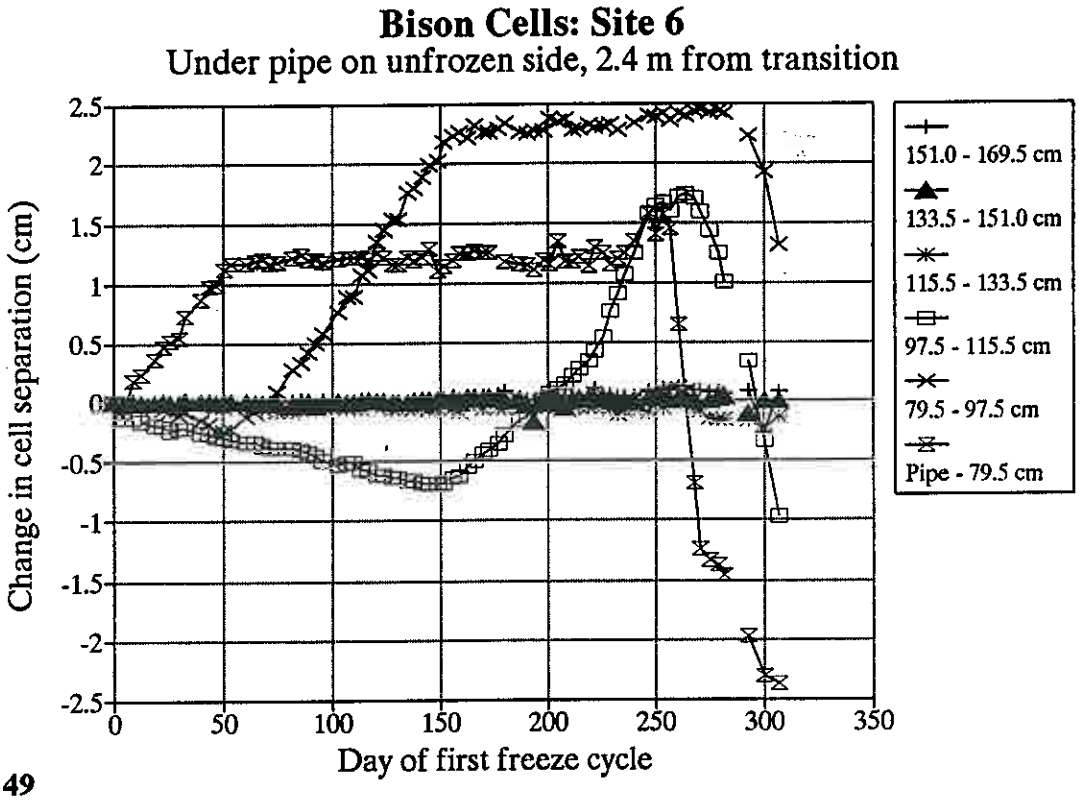


Figure 49

the transition, although the constant rate suggests that an alternative explanation may be required.

Hydrostatic profiler

This SINCO hydrostatic profiler is a prototype instrument intended to measure soil movements along a buried horizontal access tube. As its name implies, it operates on the hydrostatic principle: a change in the elevation of a pressure sensor connected to a datum by liquid-filled tubing is measured as a change in hydrostatic pressure. It was intended that this device be used to measure soil displacements immediately below the pipe. Unfortunately, problems with the stability of elevation readings have persisted with this device from the outset of the experiment. The device has been returned to SINCO in the United Kingdom (now Brainard-Kilman Ltd.), who have undertaken to determine the source of the problems.

Pipe instrumentation

Optical pipe survey

Vertical survey rods are attached to the pipe at 66 cm intervals along its full length, for a total of 24 rods. A loose plastic sleeve was placed around each rod prior to backfilling, to permit their free movement as the pipe is deformed and lifted by the heaving soil.

The shape of the pipe on certain critical dates throughout the experiment is shown in Figure 50. The latest measurement shows the pipe at its lowest elevation since initiation of the experiment, due to thaw settlement in

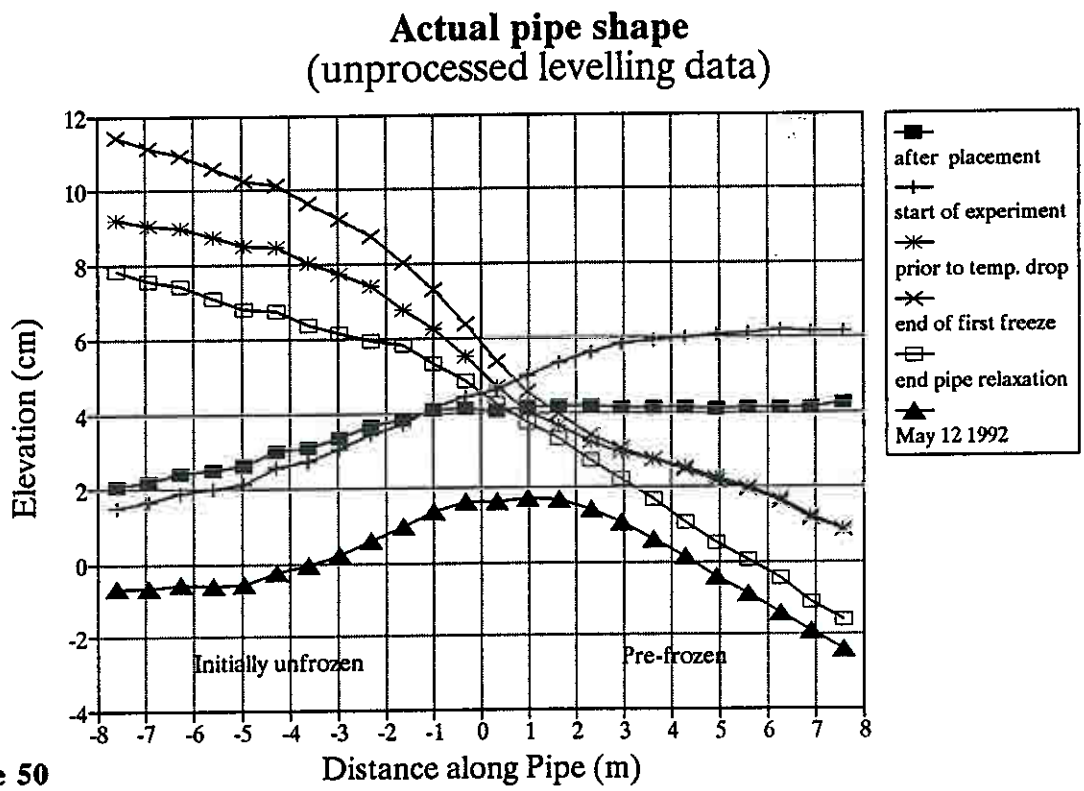


Figure 50

material consolidated by freezing.

In Figures 51 and 53 to 55, the changing shape of the pipe through different periods of the experiment is shown as the change from the shape at the start of the period. The resulting graphs do not necessarily represent how a straight pipe section would have responded over the period, since the stresses which have developed in the pipe play a role in determining its interaction with the soil.

The change in pipe shape from the start of the experiment to the end of the first freeze is shown in Figure 51. Figure 52 shows the change in elevation of the ends of the pipe throughout the experiment. In the earliest stages of freezing, the greatest curvature in the pipe was at the transition. This gradually gave way to the sigmoid curvature which was observed in the earlier Caen experiments. Pipe curvature (and hence pipe stress) was never as great as in previous experiments, however, since frost heave was about half of that experienced in the previous experiments, and because thaw settlement on the prefrozen side allowed the pipe to tilt rather than bend.

Figure 53 shows the change in elevation of the pipe during the period of lower pipe temperatures (days 215-257): in this period, the rate of frost heave was substantially increased on the initially unfrozen side, while thaw settlement was almost completely halted on the prefrozen side.

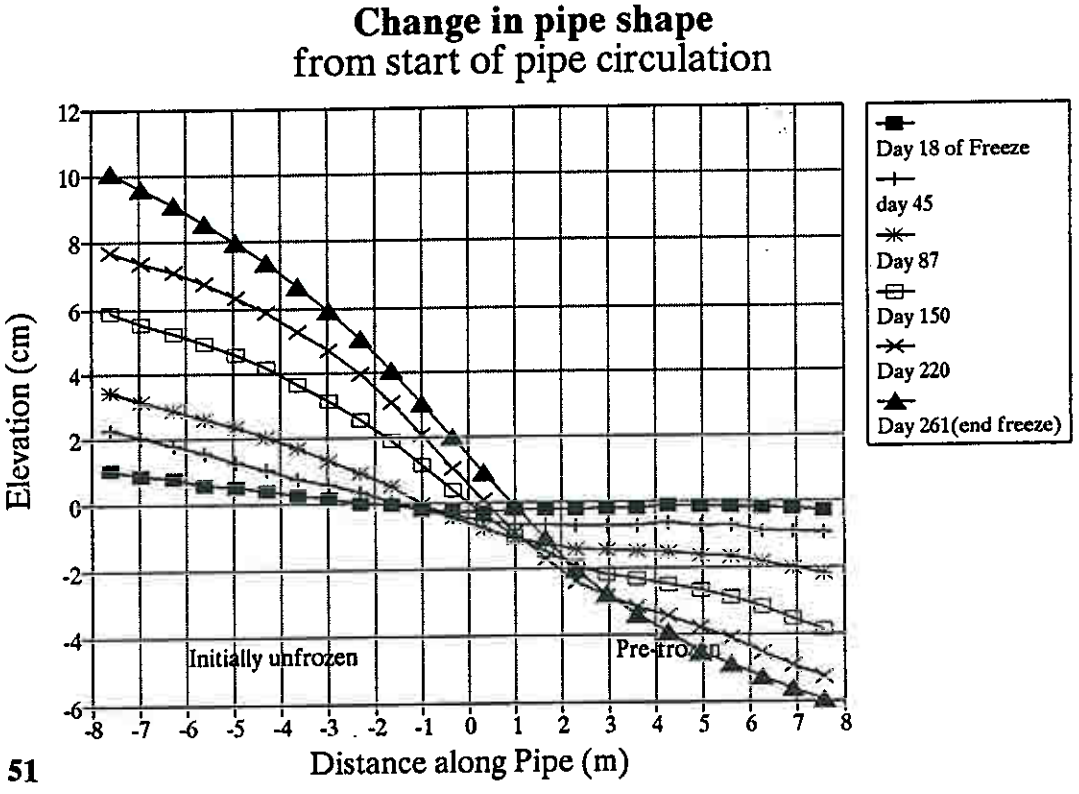


Figure 51

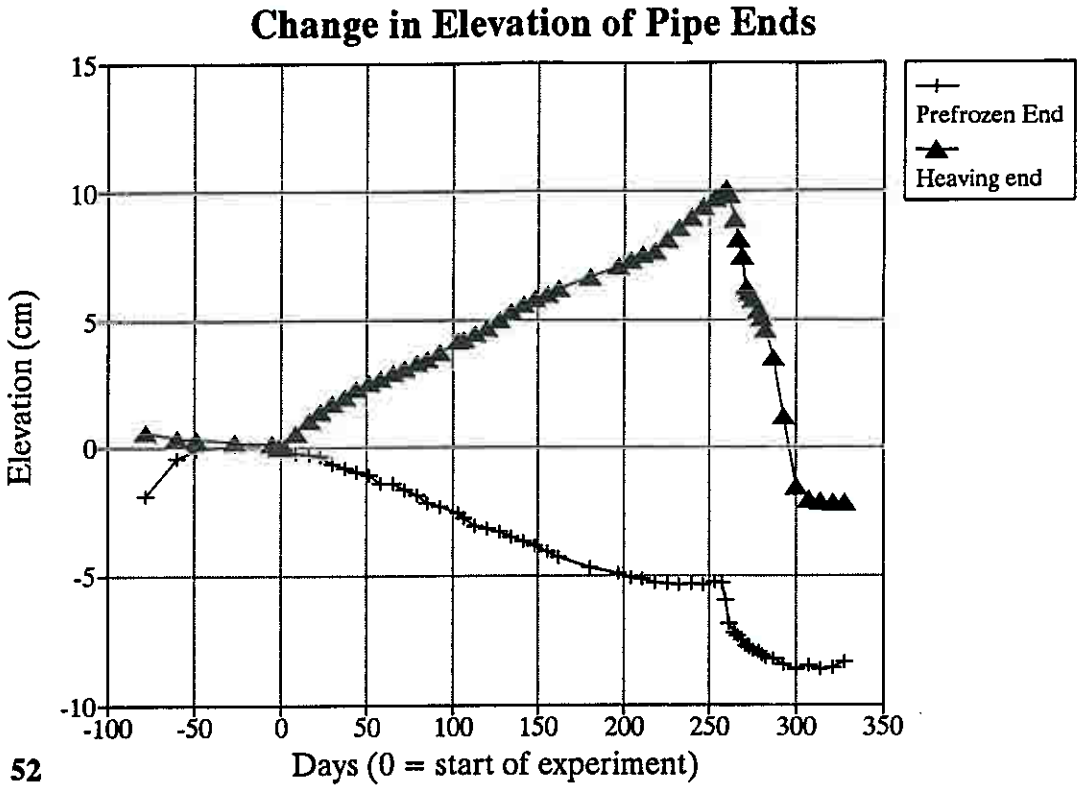


Figure 52

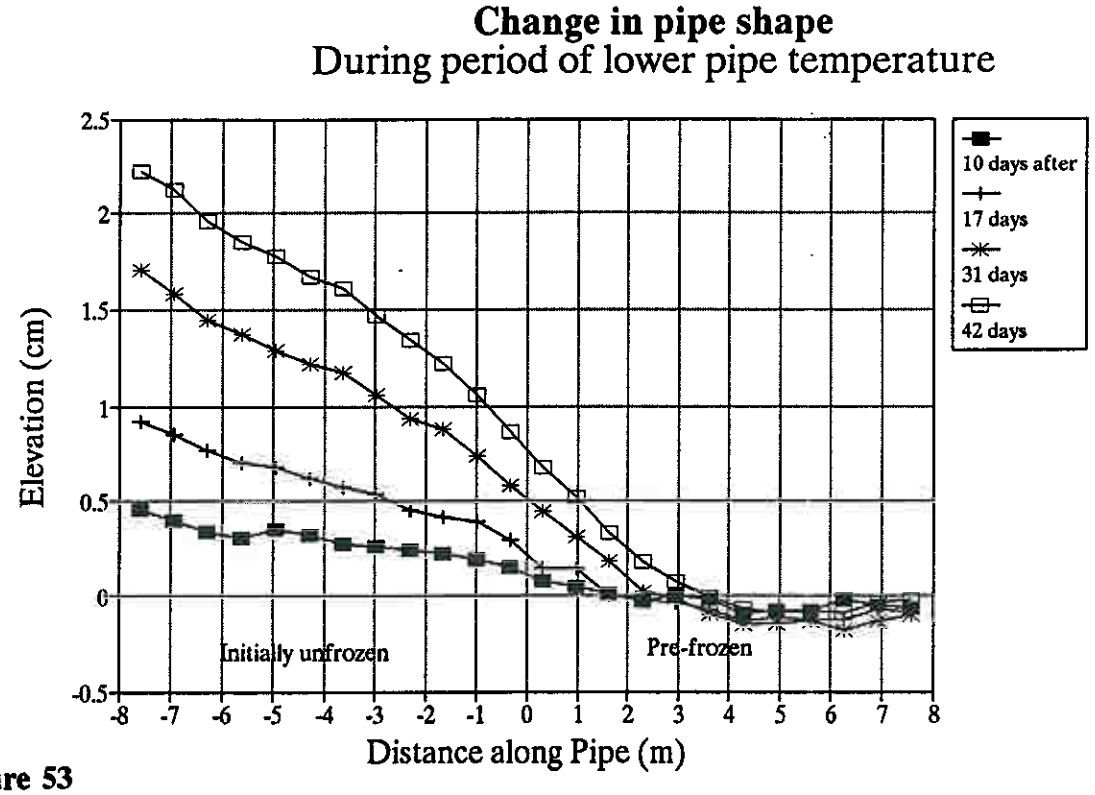


Figure 53

Figure 54 shows the change in elevation of the pipe throughout the thaw relaxation phase. The first measurement following the initiation of thaw shows uplift of the heaved pipe end, as the pipe straightened with the reduction in soil resistance. Following this the pipe straightens at the ends while settling through the thawing annulus.

Figure 55 shows the changing elevation of the pipe during the transition period (day 270). With initiation of refreezing on the prefrozen side, settlement of the pipe has been halted. On the initially unfrozen side of the experiment, settlement has been greatest at the free end of the pipe. The rate of thaw settlement has declined significantly after day 43 of the transition.

Pipe strain gauges

The pipe is instrumented with 72 120 ohm strain gauges (Micro Measurements model CEA-06-250UW-120) in two configurations:

- ten circumferential arrays of six gauges each, individually wired for quarter bridge measurements;
- six pairs of gauges, placed at the 12 o'clock and 6 o'clock positions on the pipe, wired for half bridge measurements.

Circumferential arrays extend 4 metres at 1 metre intervals on either side of the frozen transition, starting 0.5 m from the transition. Strain gauge pairs are situated at 5.5, 6.5 and 7.5 metres (1 m away from the last radial array) on

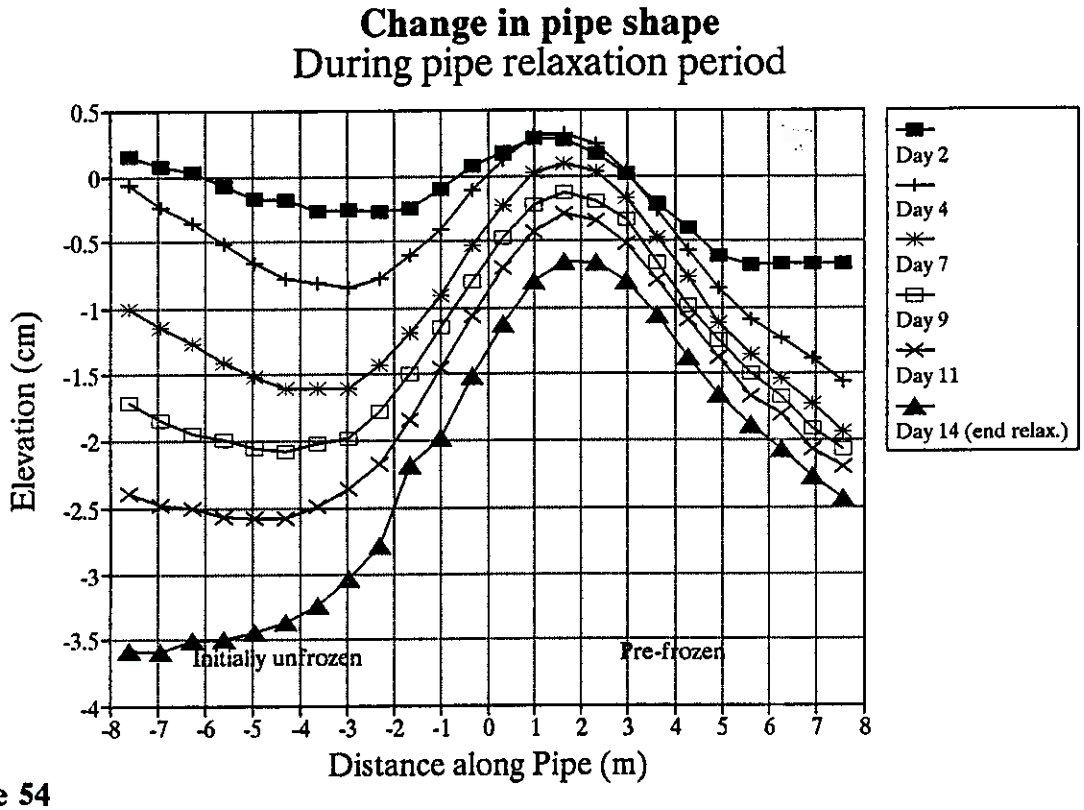


Figure 54

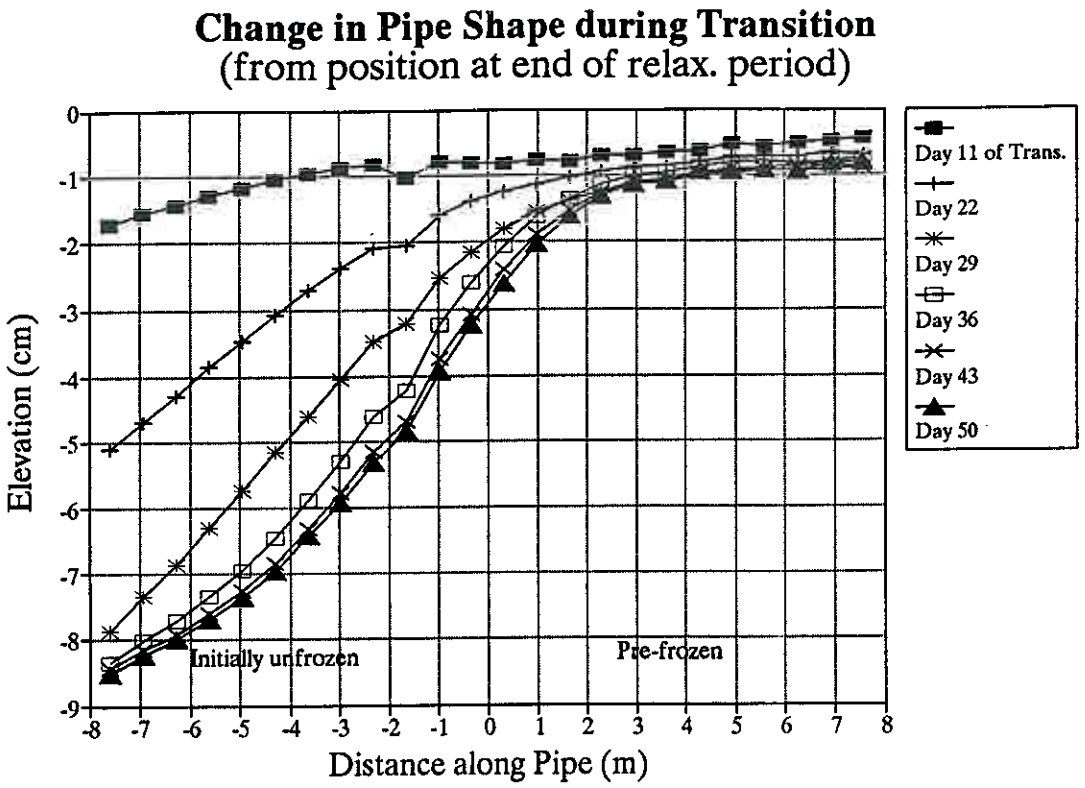


Figure 55

both sides of the transition. The strain gauge data acquisition system is now fully functional. Measurements are available for all sensors since February 27 1992 (one week prior to the end of freezing temperatures in the pipe).

Half bridge measurements

Measurements from the strain gauges toward both ends of the pipe are shown in Figures 56 and 57. Data for these strain gauge pairs are available for the entire experiment, since problems with the data acquisition system did not affect the gauges wired in a half bridge configuration. On the initially unfrozen side of the experiment, strains increased steadily through the first part of the freeze, declining by approximately 15 % when pipe temperatures were lowered. Initiation of the thaw relaxation phase resulted in a sharp reduction in strain, though strain at location B6 (5.5 m from the transition) subsequently returned to about 60% of its previous peak value reached during the freeze period. Strain at all sensors reversed rapidly at the initiation of the transition phase. The peak strains near the end of the pipe on the prefrozen side of the experiment were of approximately the same magnitude as those on the initially unfrozen side. On the prefrozen side, however, the pipe experienced its maximum strain near day 150 of the freezing period, after which strains declined at accelerating rates. Presumably, this was due to the tilting rotation of the pipe in the soil as a result of the ongoing thaw settlement at the base of the prefrozen section.

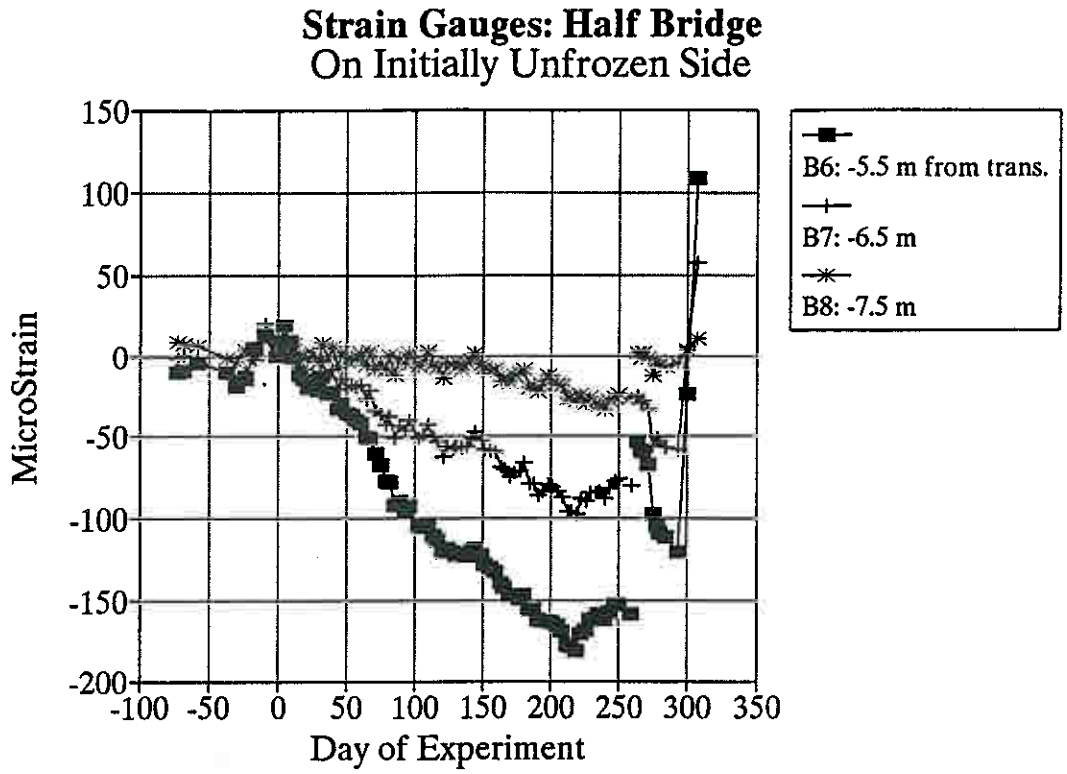


Figure 56

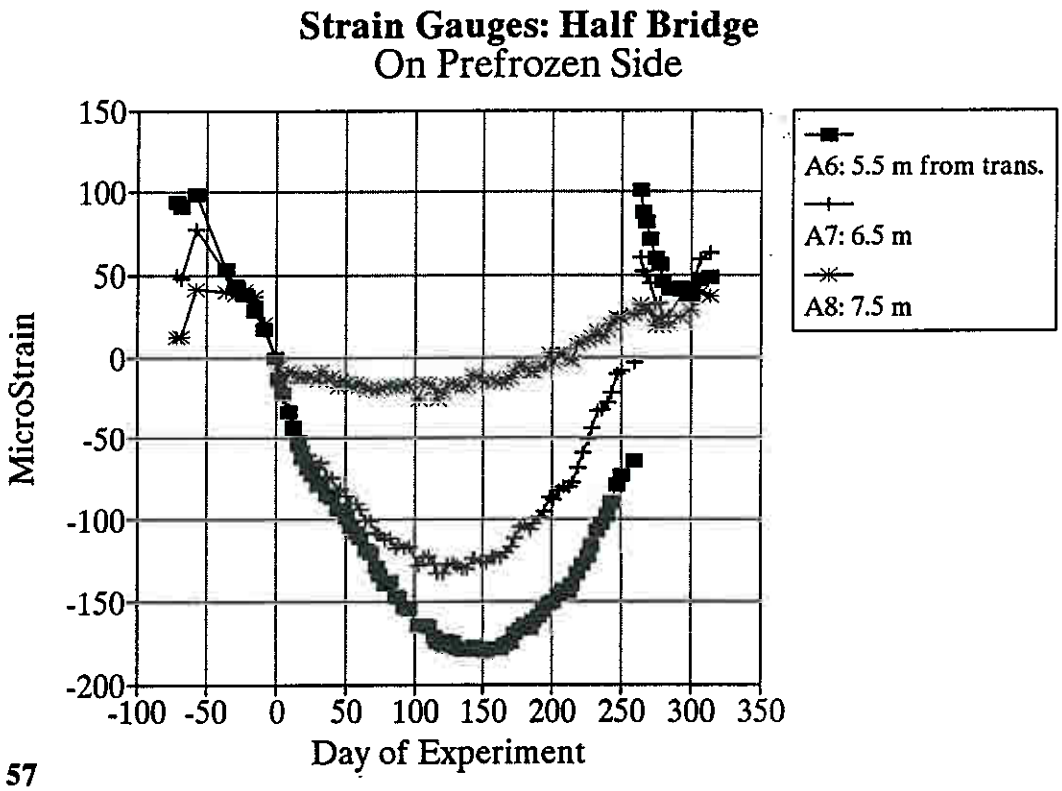


Figure 57

Quarter bridge measurements
Manual gauge measurements were taken at the time of gauge installation. These measurements were taken using a balanced manual bridge system, in which strain is determined from the resistance required to balance a wheatstone bridge, with the same bridge circuit for all strain gauges. The data acquisition system determines strain by measuring the voltage across an *unbalanced* wheatstone bridge, with a unique bridge for each strain gauge. The differences in the two measurement systems make it impossible to relate the measurements taken at the time of installation with those taken with the data acquisition system. Instead, an attempt has been made to relate measured strains to pipe curvatures determined from the optical survey data, making it possible to estimate the peak strains experienced by the pipe (at the end of the freezing period).

Measurements for all 10 radial strain gauge arrays are shown in Figures 58-67. On the initially unfrozen side of the experiment (Figures 58-62), strains peak and start to reverse before the end of the thaw relaxation period. (One exception is site B1 [0.5 m from the transition], which behaves similarly to the gauges on the prefrozen side of the experiment.) This continues until about day 300, after which strains again reverse and double the peak values measured during the relaxation period. At site B2 (1.5 m from the transition) the strains almost return to their original value before this reversal.On the prefrozen side of the experiment (Figures 63-67), the peak strain during the thaw relaxation period tends to correspond with the end of the period. In the early part of the transition there is a slight reversal of the trend, after which strains again continue to increase. One significant exception to this behaviour was at strain gauge location A5 (4.5 m from the transition), which behaves similarly to the strain gauges closer to the end of the pipe, due the straightening of the pipe as the soil loses strength.

Comparison with the pipe levelling data suggest that the changes in the figures over the period from day 290 to 310 appear to correspond to the "bottoming out" of the pipe.

As a first approximation, the change in strain which has occurred during thaw relaxation and the transition period is an indication of the stress state of the pipe at the end of the freeze. Inspection of the data for the radial strain gauge arrays show that the strain measurements since the initiation of the thaw relaxation phase has peaked or the rate of change has significantly slowed down for most gauges.

Strains along the pipe for the end of the thaw relaxation period and for the most recent configuration of the pipe (when settlement has slowed significantly) are shown in Figure 68. In this figure, the data for the ends of the pipe (half bridge gauges) reflect the change in strain which has occurred since the quarter bridge measurements have been taken, while the quarter bridge measurements are the average of the 12 o'clock and 6 o'clock gauge readings. On both sides of the pipe, the total change in the maximum strain to May 5 is about two times the change in strain during the thaw

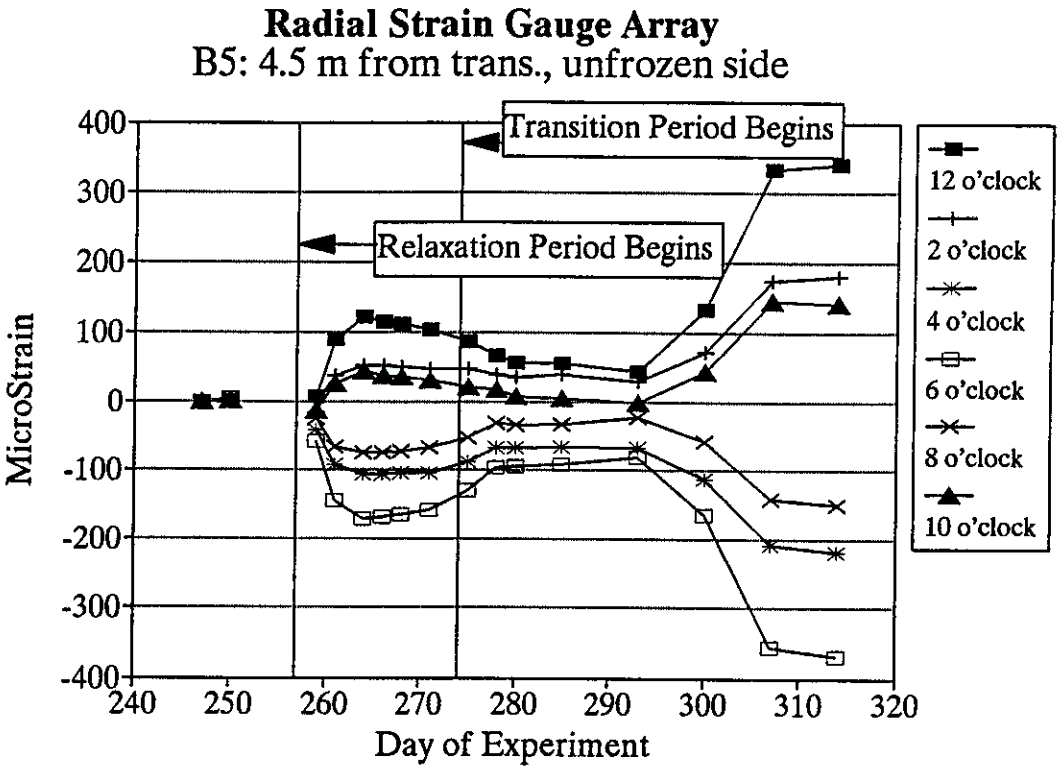


Figure 58

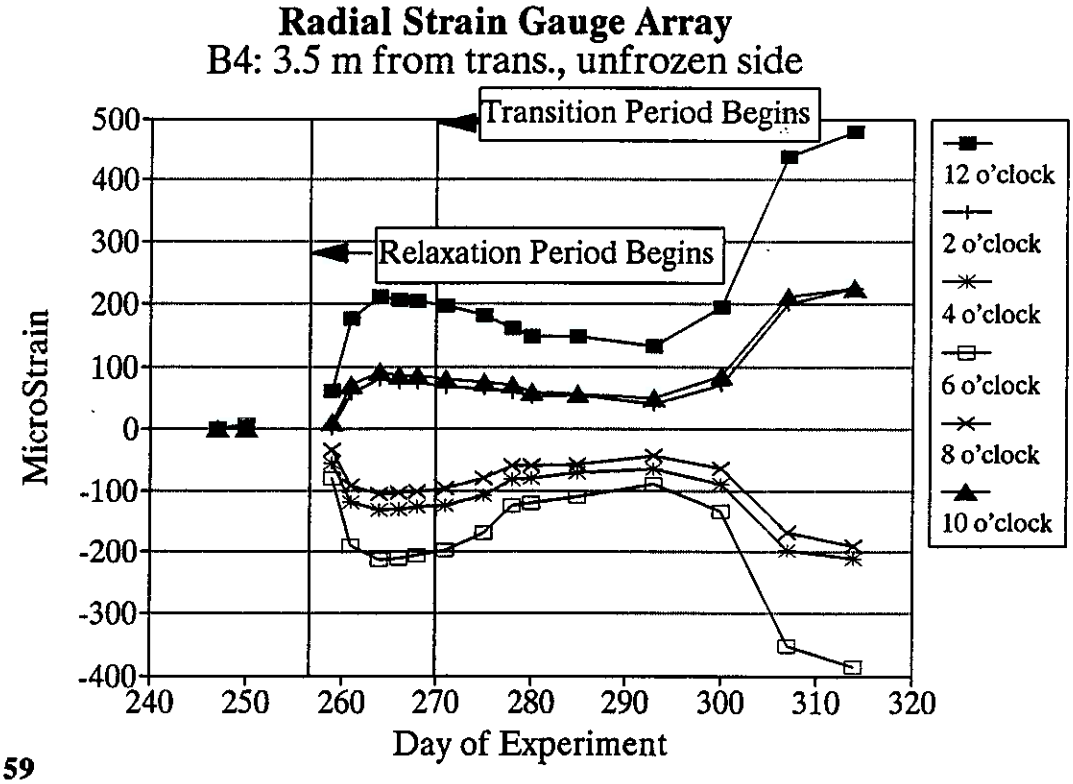


Figure 59

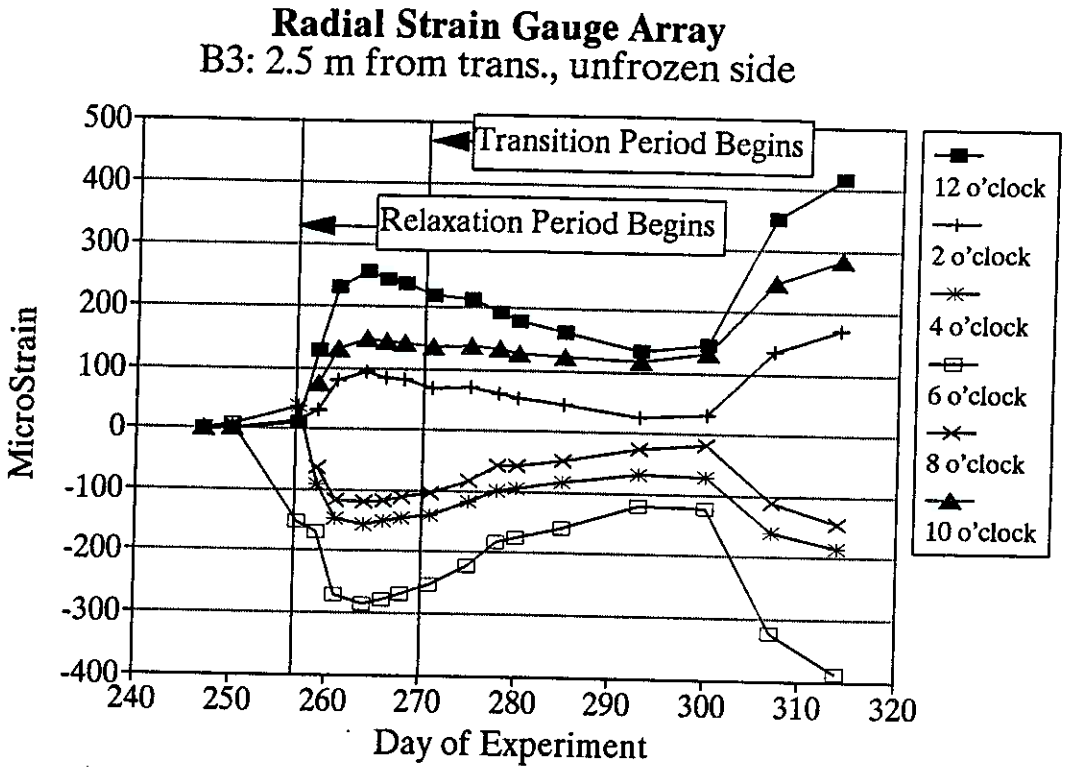


Figure 60

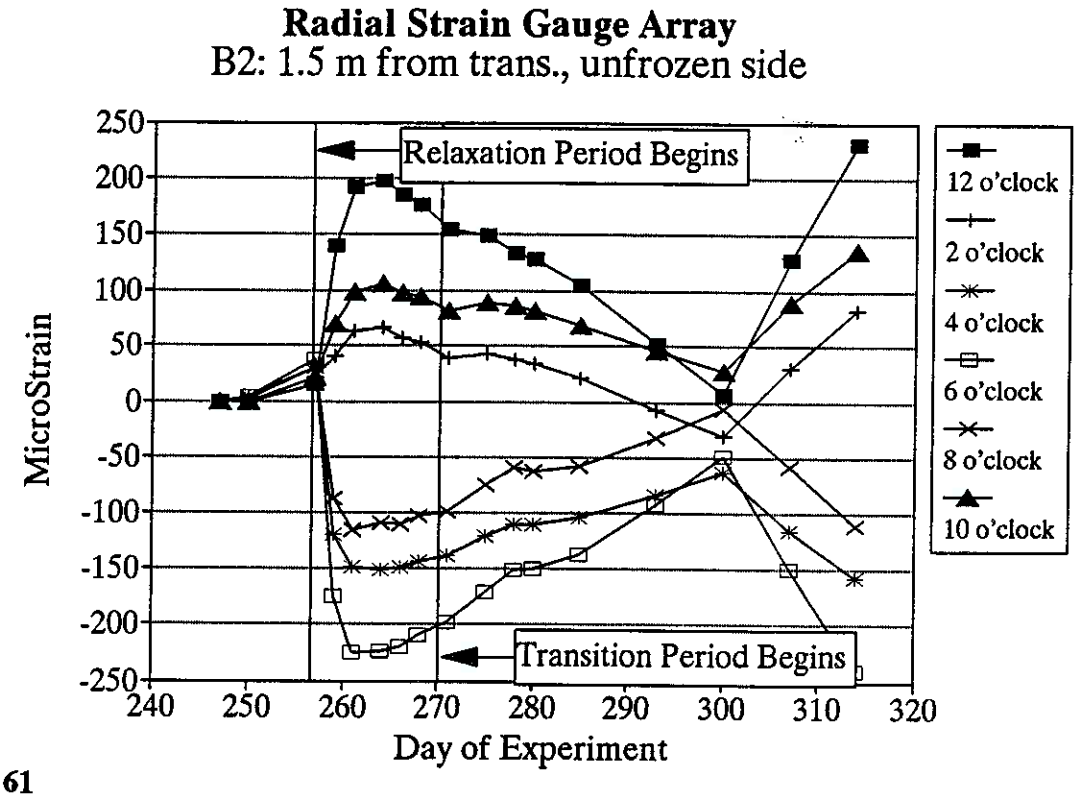


Figure 61

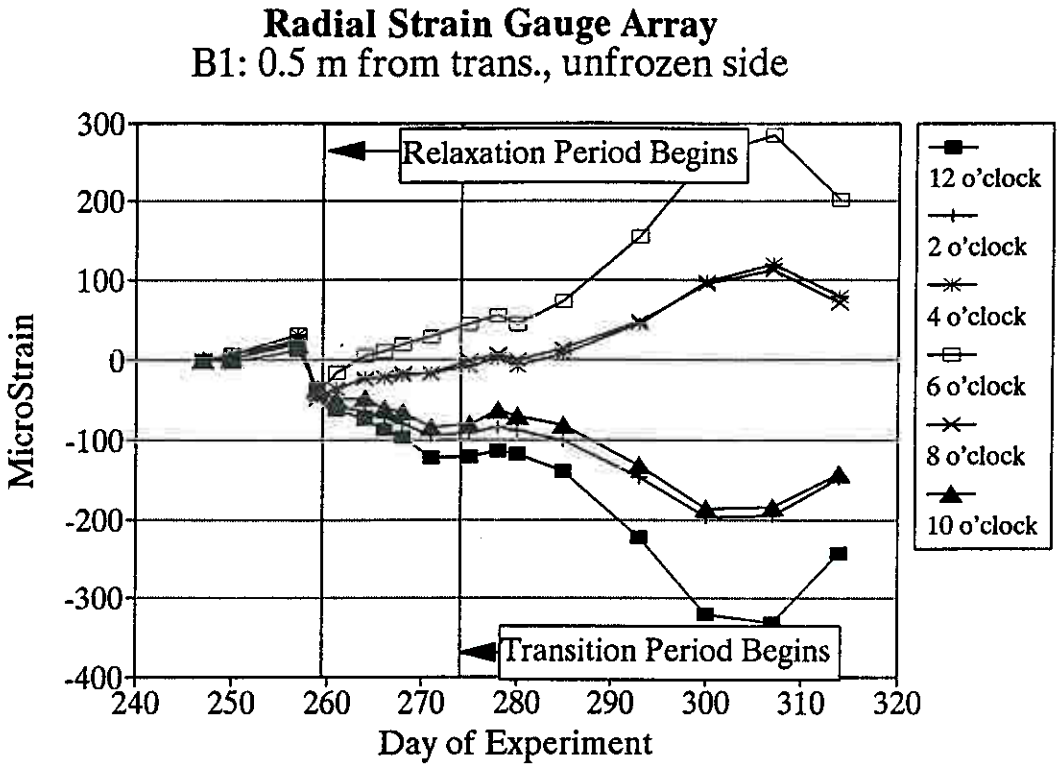


Figure 62

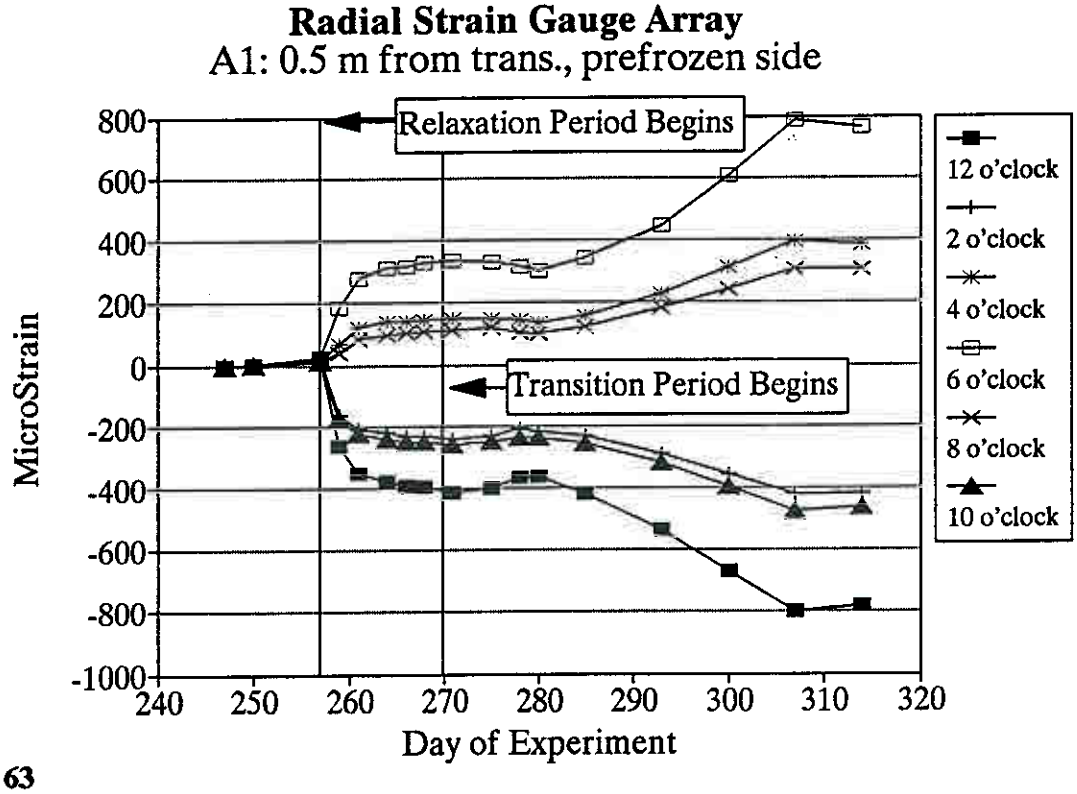


Figure 63

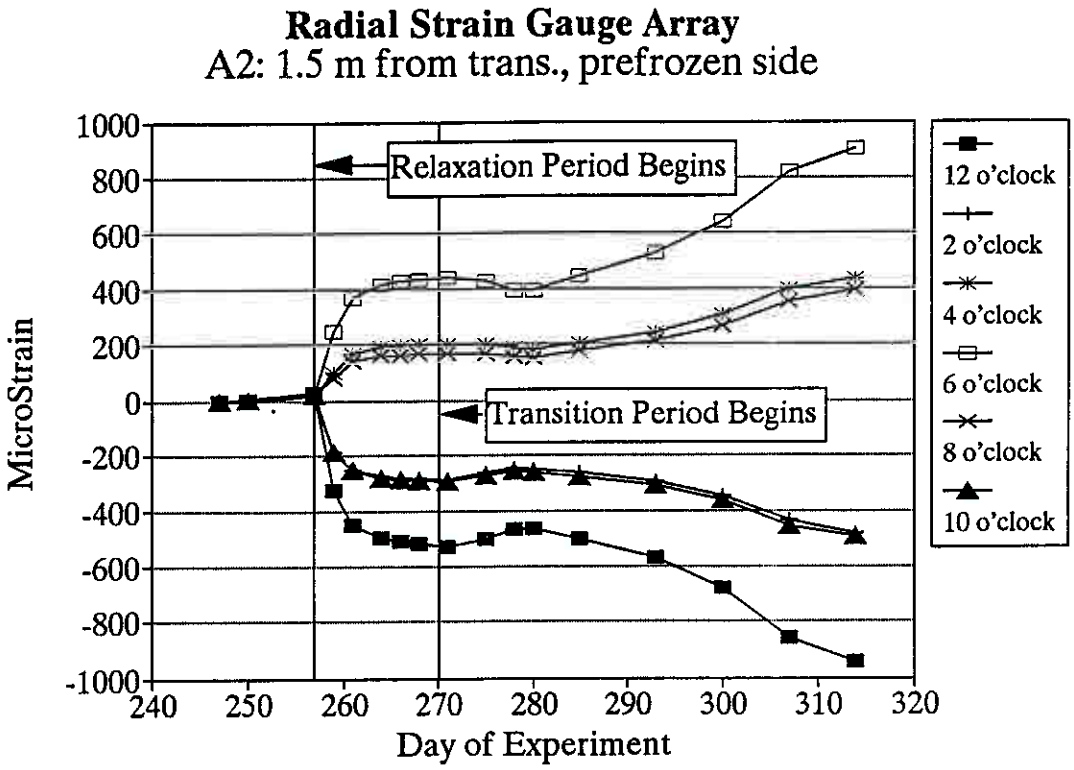


Figure 64

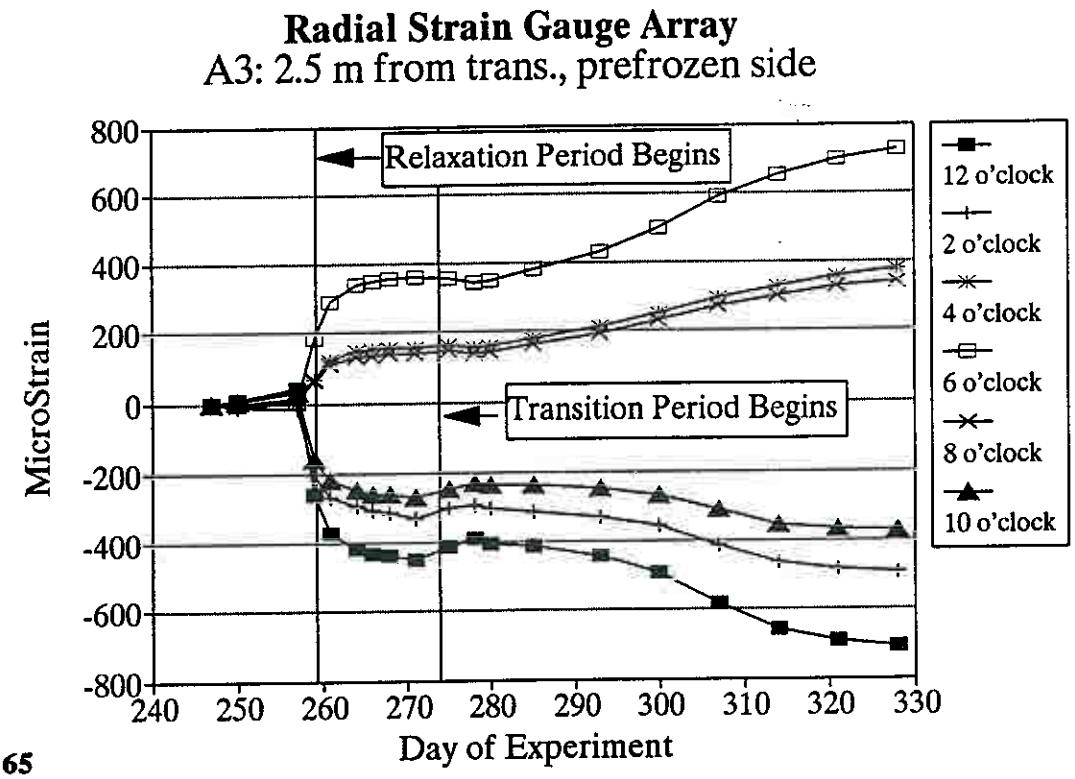


Figure 65

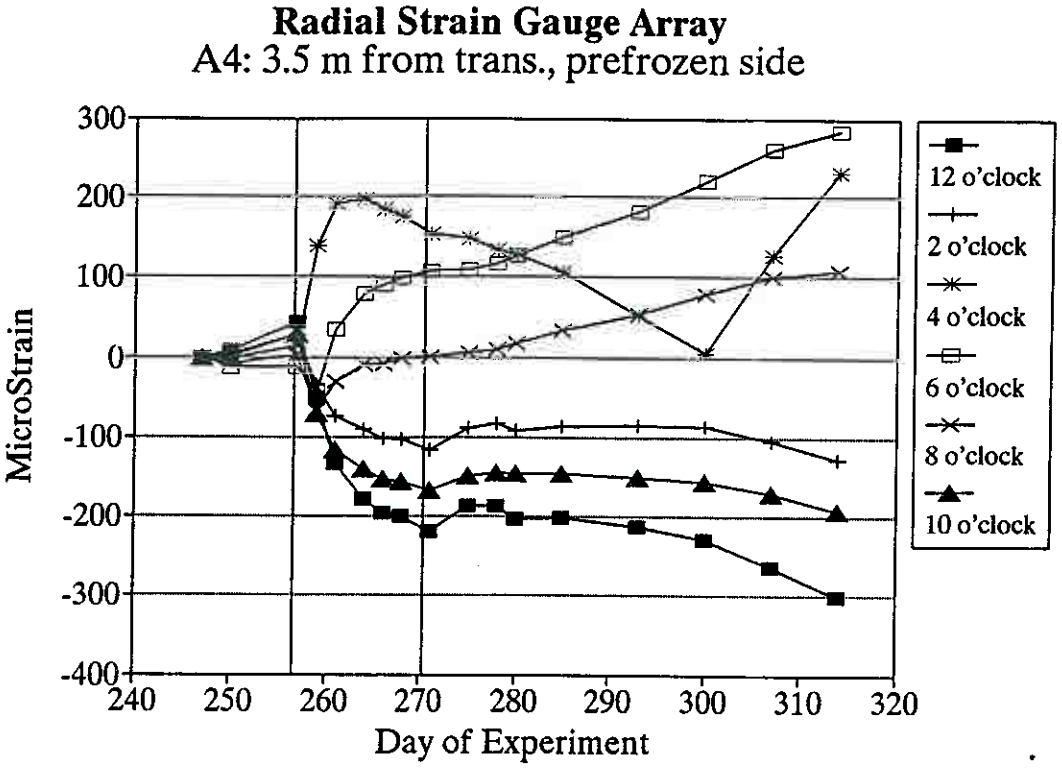


Figure 66

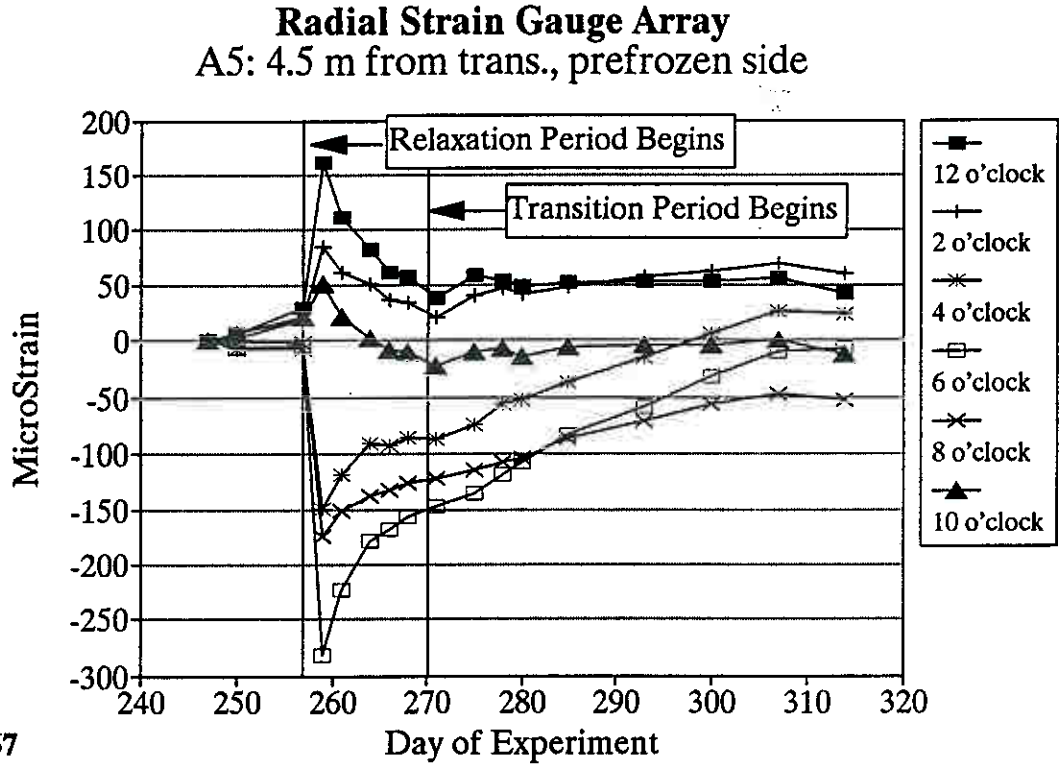
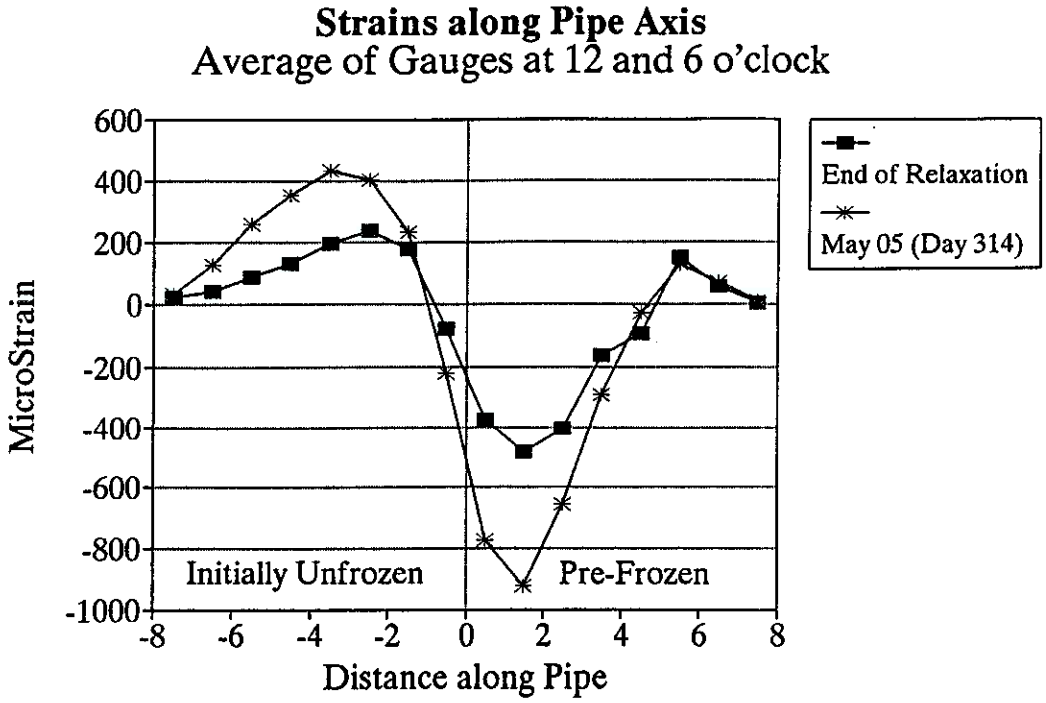


Figure 67



* Strain zero reference is March 01 1992 (day 248)
1 week befor end of Freeze.

Figure 68

relaxation period. The peak strain on the prefrozen side of the experiment is approximately twice as great as on the initially unfrozen side of the experiment.

Estimated maximum pipe strains

One of the principal aims of the experiment is to determine the stresses in the pipe as a result of movements within the soil. Strain is measured via resistance strain gauges by calculating the change in resistance (equivalent to the change in strain) from the initial value. Because the pipe does not return to its original shape and position at the end of the freeze-thaw cycle, the strain gauge bridge measurements do not allow direct determination of the strain in the pipe at the end of the freeze, when strain is assumed to have reached its maximum. It is possible to estimate the strain at this, and any other, time through the experiment by using the optical survey data for the pipe, making use of the proportionality between strain and the curvature of the pipe.

Pipe shape (or changes in pipe shape) was modelled with eighth degree polynomial curve fits to the levelling data. Curvature was then estimated using the second derivative of the polynomial. This approach works well for the central portion of the pipe, with significant errors at the ends of the regression (where the procedure is less constrained by the data). Figure 69 shows measured strain and the change in pipe curvature over the period March 3 - May 19 1992, and confirms the relationship between these quantities. The relationship is not perfect however,

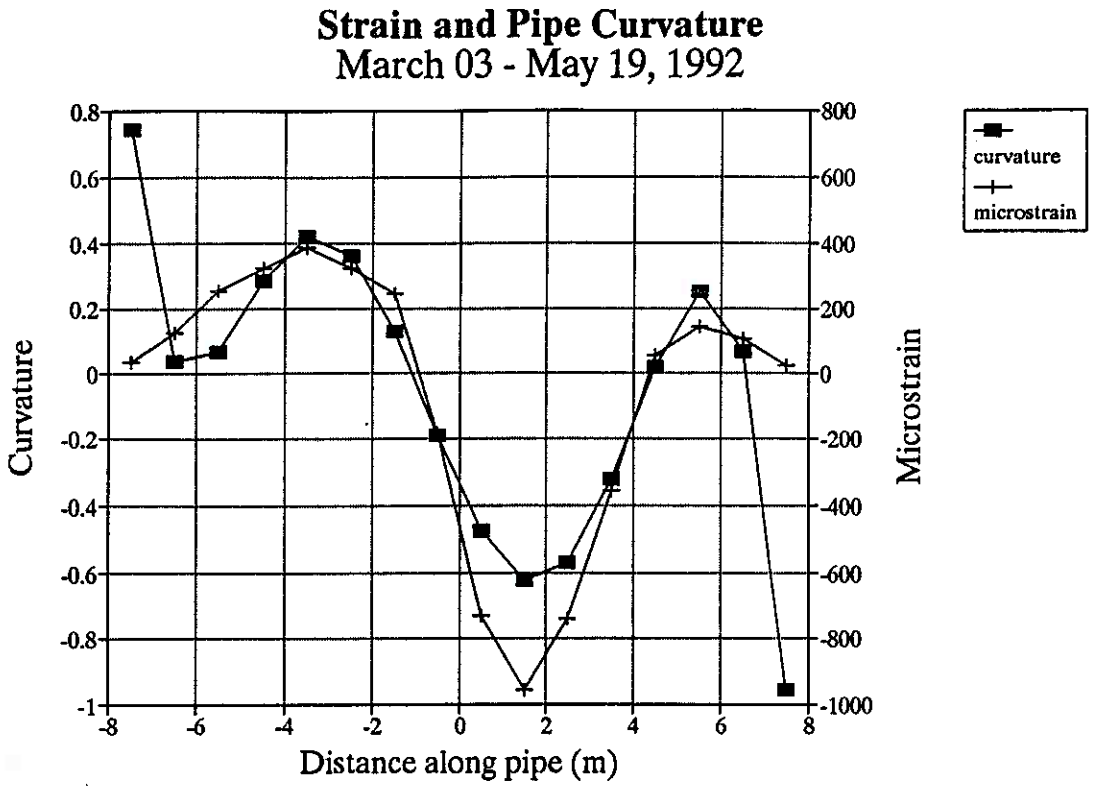


Figure 69

since the ratio of strain to curvature is smaller when strain is negative than when strain is positive. This may be due to the distance between the pipe's central axis and the pipe wall, where the strain measurement is taken, or to sources of stress not related to pipe curvature. The modelled curvatures at the ends of pipe are simply an artifact of the regression procedure, and are erroneous. Excluding the data for the two endpoints, the relationship between strain and curvature is shown in Figure 70.

First and second degree polynomial regression of this curvature-strain relationship was used to generate estimates of strain based on the latest survey measurements (Figure 71). The fit is not particularly good at the points of peak strain. In addition to this problem, the relationships will not be reliable beyond the limits of the data, which the curvature at the end of the freeze cycle would be.

Figure 72 shows the calculated changes to the curvature of the pipe for three dates: between the start of the experiment and the end of freezing; between the start of strain measurements and the latest measurement; and between the start of the experiment and the latest measurement. Using these curves together with the measured strain for the latest curve, the strain between the start of the experiment and the end of freezing can be estimated for each point on the pipe by multiplying the ratio of the curvatures at any two times by the measured strain at one of those times.

Figure 73 shows three different

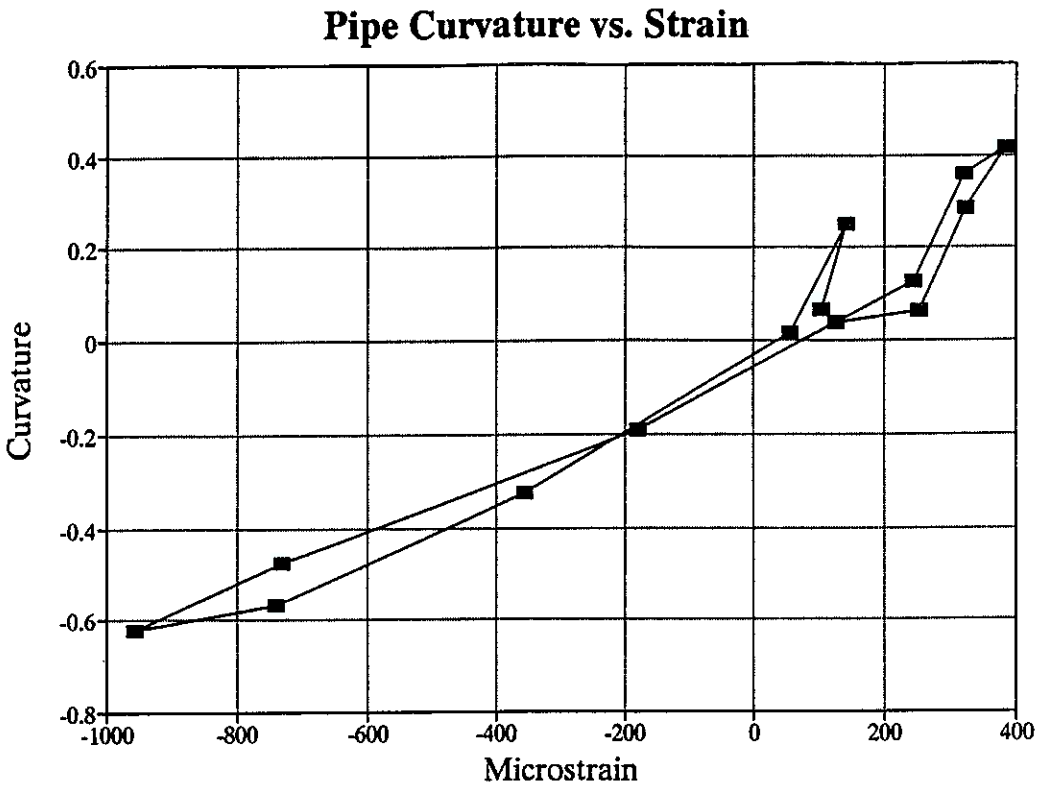


Figure 70

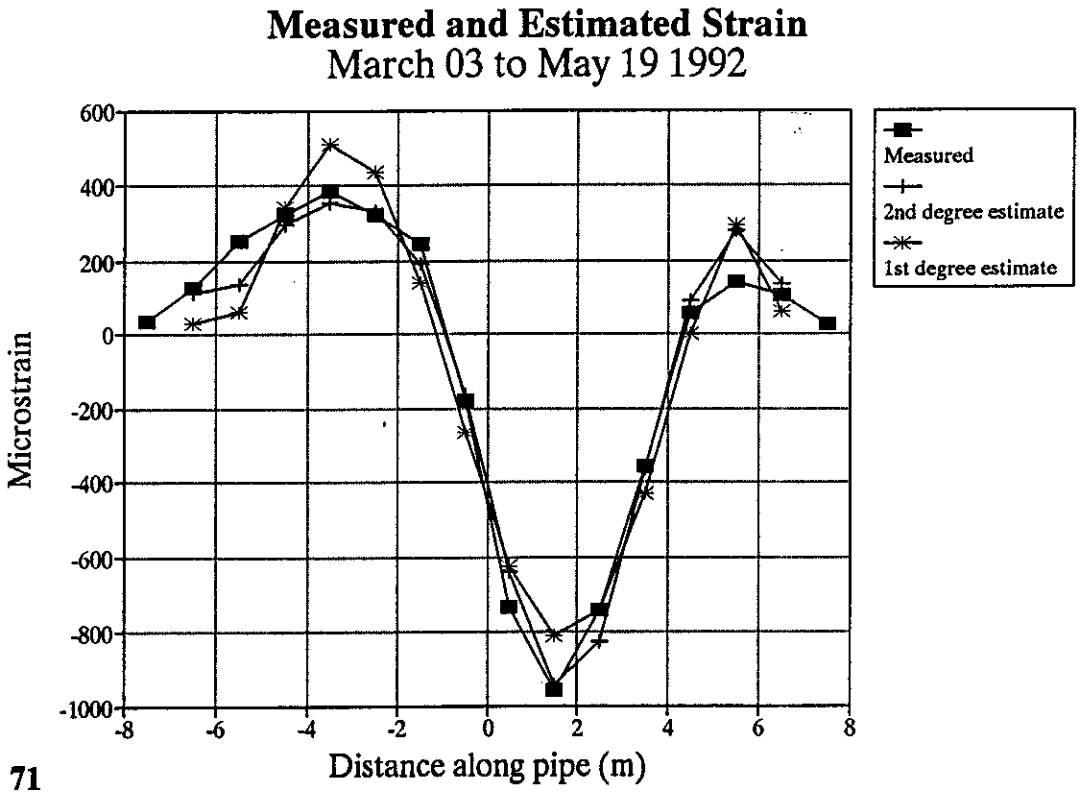
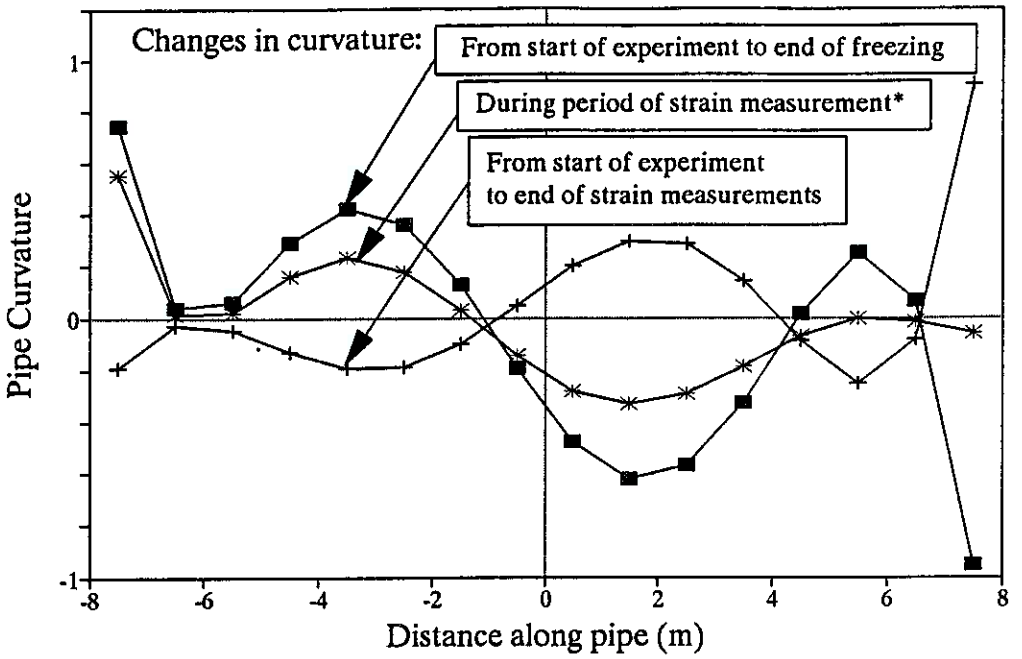


Figure 71

Pipe Curvature
estimated from levelling data



* March 3 1992 to May 19 1992

Figure 72

Estimated Strain at end of Freeze
from curvature/strain relationships

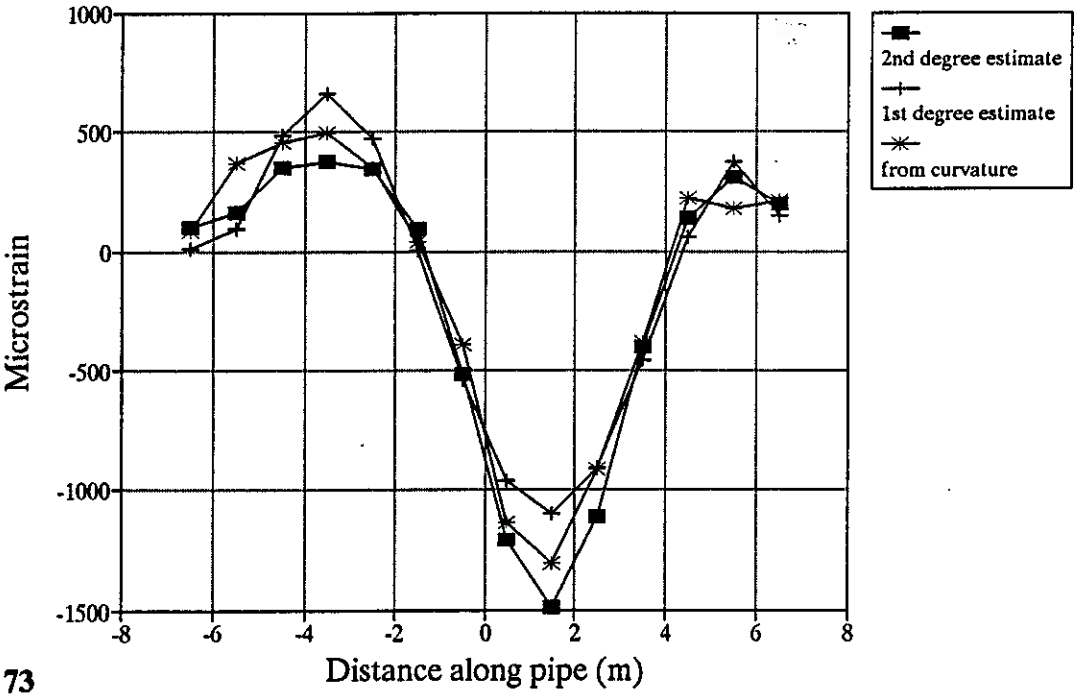


Figure 73

estimates of the distribution of strain along the pipe at the end of the first freeze. Results from all three methods are similar in form but differ in magnitude: The method based on the curvatures at each point rather than on a more general curve-strain relationship appears to provide the best estimate.

Pipe-soil interaction

Longitudinal shear stress

Two devices were installed to measure longitudinal shear between the pipe and the soil. The "LVDT" device is intended to measure the movement of the pipe relative to soil unaffected by the shearing forces. The steel strip device is intended to measure the shear within the soil immediately adjacent to the pipe. Both are installed approximately 2 m from the frozen interface, on the unfrozen side.

"LVDT" device

This device consists of a linear potentiometer attached to two "fixed" points : one on the pipe and the other in the soil some distance from the pipe. The linear potentiometer consists of a piston and sleeve with universal joints on both parts for attachment. At one end, the universal joint attaches to a steel strap connected rigidly to the pipe. At the other end the potentiometer attaches to a soil anchor as described above. A survey rod is attached to the anchor, to allow determination of the vertical heave component of the movements of the potentiometer.

Figure 74 shows the extension of the LVDT device. The device has registered a change in its extension over the entire freezing and thawing period of 4 mm, mostly confined to the initial freezing in place and thaw settlement of the soil. After the initial freezing in of the device, movement of about 0.1 mm was recorded until the initiation of the relaxation phase.

"Steel strip" device

This device, based on Williams (1957), consists of a steel strip instrumented with 350 ohm strain gauges (Micro-Measurements model CEA-06-125UW-350) in paired half bridge configuration, installed horizontally radial to the pipe. The strip bends when the adjacent frozen soil is deformed. Analysis of strain gauge measurements from the strip can be used to measure shear within the soil adjacent to the pipe. The end farthest from the pipe is attached to an anchor as described above. The end adjacent to the pipe is free, and is installed 1 to 2 mm from the pipe surface (that is, it does not touch the pipe).

Results from the strain gauges attached to this device are shown in Figure 75. Two of the gauges failed after 150 days of freezing, while the gauge pair which has registered the greatest strain has given erratic results since that date, though measurements appear to be stable at present.

The device requires calibration before strain measurements can be interpreted: a specimen of the steel used in the strip will be tested to determine its mechanical properties. In addition, identical strain gauges will be installed on a sample steel strip to calibrate gauge response to strip curvature in the laboratory.

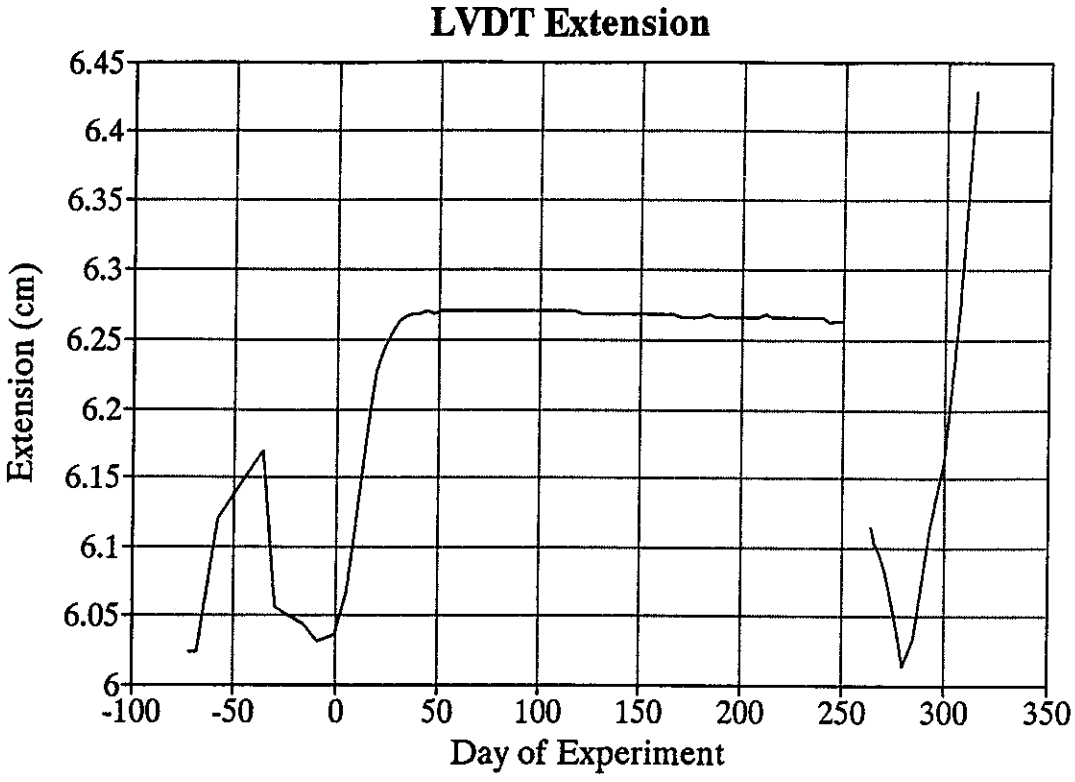


Figure 74

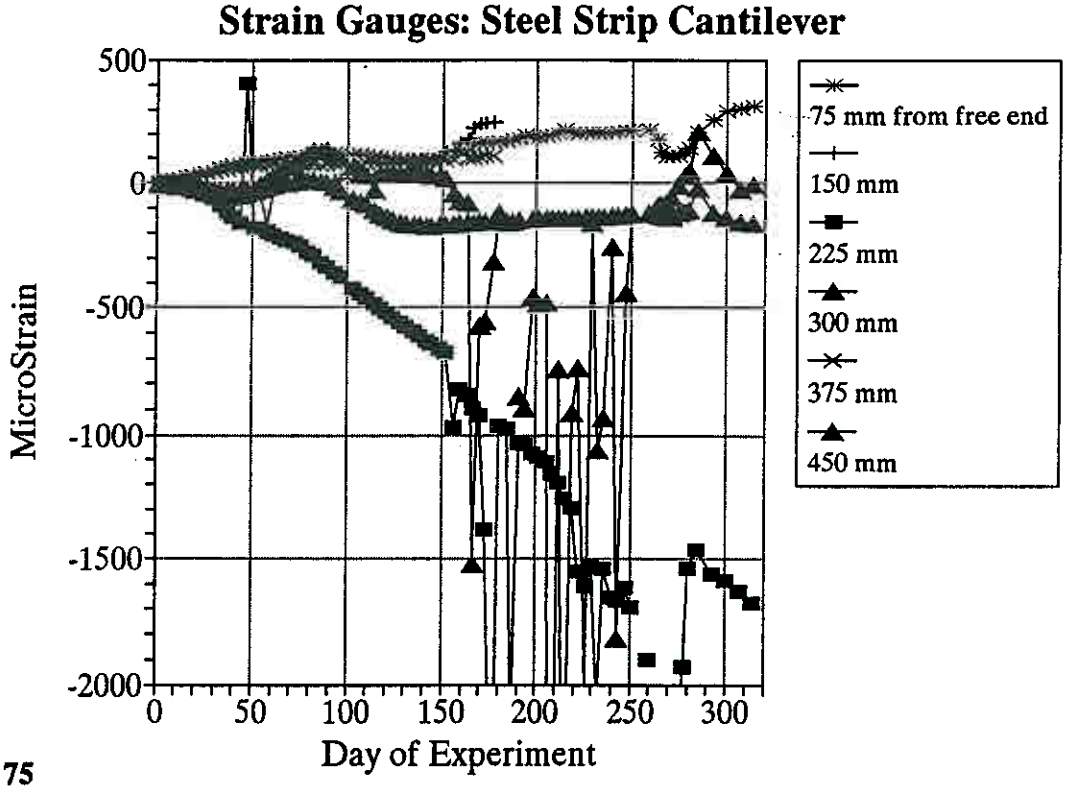


Figure 75

References

Dallimore, Scott R., 1985. Observations and predictions of frost heave around a chilled pipeline. M.A. Thesis, Department of Geography, Carleton University, Ottawa, Canada. 110 p.

Geotechnical Science Laboratories, 1982. Feasibility study for stresses in a pipeline buried in freezing soil. Final report to the Department of Energy, Mines and Resources, Earth Physics Branch, December 1982. 36 p.

Geotechnical Science Laboratories, 1983. Investigation of soil freezing in association with a buried chilled pipeline in a large-scale test facility -phase 2 and interim report - analyses of stresses developed in pipeline buried in freezing ground august 1983. 41 p.

Geotechnical Science Laboratories, 1984a. Analyses of stresses developed in pipelines buried in freezing ground. Final report to the Department of Energy, Mines and Resources, February 1984. 64 p.

Geotechnical Science Laboratories, 1984b. Experimentation sur le gel d'un sol et d'une canalisation enterree et refroidie dans une installation d'essai de grandes dimensions, 3e phase. Rapport Final pour l'Energie Mines et Ressources, Direction de la Physique du Globe, September, 1984. 73 p.

Geotechnical Science Laboratories, 1985. Analyses of stresses developed in pipelines buried in freezing ground. Final report to the Department of Energy, Mines and Resources, Earth Physics Branch, May 1985. 44 p. (incl. 16 figs. and 1 plate)

Geotechnical Science Laboratories, 1986.Investigations of frost heave as a cause of pipeline deformation. Final report to the Department of Energy, Mines and Resources, Earth Physics Branch, January 1986. 71 p.

Geotechnical Science Laboratories, 1986.Thermodynamics and mechanics of freezing soil around a pipeline. Final report to the Department of Energy, Mines and Resources, Earth Physics Branch, November 1986. 111 p.

Geotechnical Science Laboratories, 1988a.The third freeze cycle of the Canada-France ground freezing experiment. Final report to the Permafrost Research Section, Terrain Sciences Division, Geological Survey of Canada (Department of Energy, Mines and Resources) January 1988. 78 p.

Geotechnical Science Laboratories, 1988b. Spatial variability of heave around a pipeline and the effects of repeated freezing and thawing. Report to the Permafrost Research Section, Terrain Sciences Division, Geological Survey of Canada (Department of Energy, Mines and Resources) July 1988. 35 p.

Geotechnical Science Laboratories, 1989. Canada-France pipeline-ground freezing experiment: phase viii, fourth freeze cycle.Report to Permafrost Section, Terrain Sciences Division, Geological Survey of Canada (Department of Energy,Mines and Resources) July 1989. 81 p.

Williams, P.J. 1957. The direct recording of solifluction movements. American Journal of Science, Vol 255, pp. 705-714.

Williams, P.J. 1992. Gas pipelines and the challenge of the cold regions: an experimental study. Proceedings of the International Conference on Pipeline Reliability, Vol. 1. Calgary, Alberta, Canada, 2-5 June 1992. pp. II-2-1 to II-2-12.

Williams, P.J., D.W. Riseborough and M.W. Smith 1992. The France-Canada joint study of an experimental pipe line by differential frost heave. Proceedings of the Second(1992) International Offshore and Polar Engineering Conference. San Francisco, U.S.A., 14-19 June 1992. pp. 40-45.