The Third Freeze Cycle of the Canada-France Ground Freezing Experiment

GEOTECHNICAL SCIENCE LABORATORIES

Carleton University

The Third Freeze Cycle of the Canada-France Ground Freezing Experiment

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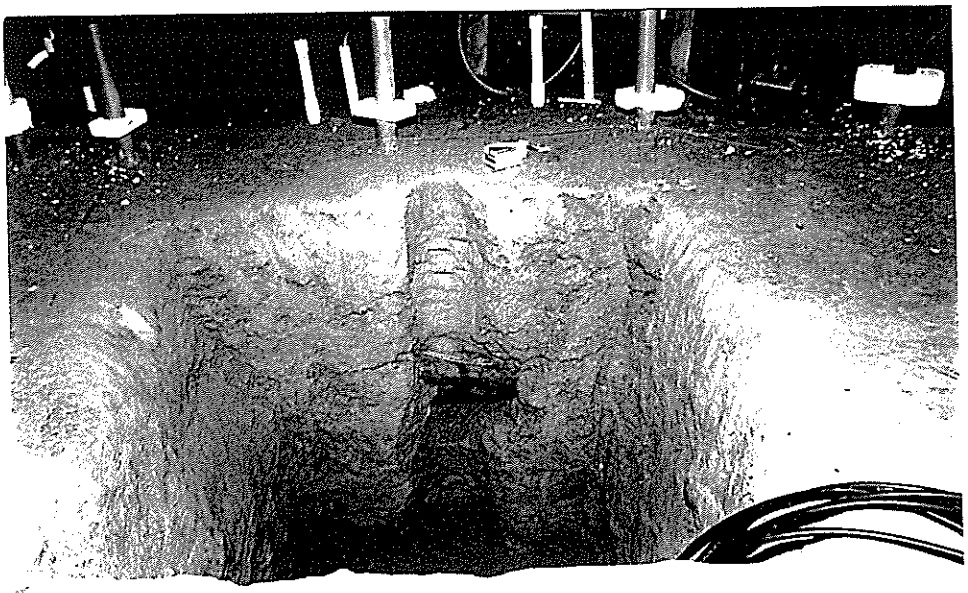

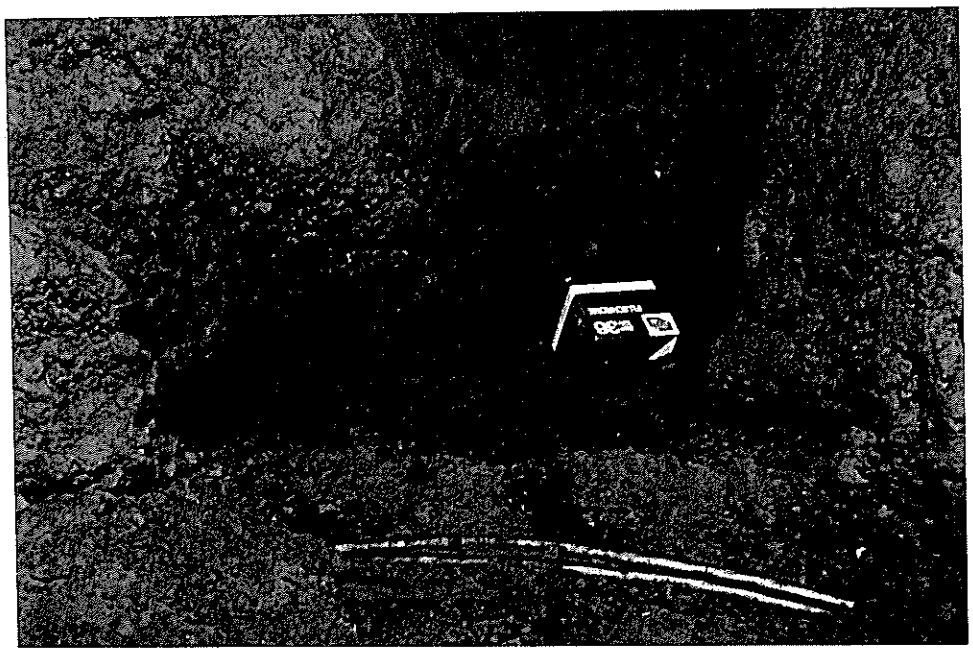

FRONTISPIECE

A cavity was discovered beneath the pipe which persists from one freeze-thaw cycle to the next. As far as can be ascertained currently, it extends along much of the length of the pipe in the silt section. It is known that cavities can form below boulders in natural conditions, where they are part of the irreversible displacements associated with frost heave and which give rise to the phenomenon of growing stones.

The upper picture is a general view of an excavation beside the pipe, revealing the cavity. The lower picture shows the cavity in close-up. The film package indicates the size of the opening. The pair of wires seen above the cavity are resting against the 27 cm diameter pipe, the lower edge of which is against the film carton.

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Forward

This report summarizes the findings of the third freeze-thaw cycle of the Canada-France pipeline ground freezing project. The purpose of the project is to study the effects of ground freezing and pipeline interaction. The project is located in a controlled environment facility at Caen, Normandy France.

Findings from previous freeze-thaw cycles are reported in the literature cited in the bibliography. This report was prepared by D.E. Patterson (Project Manager, Ottawa), D.E. Lawrence (former Project Manager, Caen) and Dr. P.J. Williams (Principal Investigator) with important contributions from Dr. M.W. Smith (Co-Principal Investigator). The efforts of the Project Managers in France, members of the Centre du Geomorphologie, CNRS and Laboratoire Central des Ponts et Chaussees are greatly appreciated.

The Canada-France project is comprised of a team of Canadian and French scientists, graduate students and technicians. The continued assistance of M. M. Dupas (LCPC) is particularly appreciated. The project as a whole is supervised by a scientific committee. The members and their affiliations are listed below.

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I. The Third Freeze Cycle of the Canada-France Ground Freezing Experiment

1.1 General

As discussed in previous reports, a 273 mm by 18 m long pipeline was installed in a temperature controlled facility located, in Caen France, early in 1982. The facility consists of refrigerated hall measuring 18 m by 8 m with independent temperature control for the hall and the pipe. Adjacent rooms accommodate instrumentation and mechanical equipment. The hall contains two soils of differing frost susceptibility (sand and silt) with each soil occupying one half of the facility (see Figure 1.1 and 1.2). The pipe was buried 30 cm below the soil surface along the centre axis of the facility.

The study has shown that the freezing of soil around the buried chilled pipeline results in heaving of the soil and the pipeline. Since the pipe traverses soils of differing heave susceptibilities, differential heave occurs which leads to deformation of the pipe and the creation of substantial stress within the pipe.

During thaw cycles, the pipe does not settle back to its initial position after freezing. In fact, the three freeze-thaw cycles have produced a progressive jacking of the pipe upward toward the soil surface and thus subsequent freeze cycles deform an already displaced pipe. The accumulated deformations associated with a number of freeze-thaw cycles could permanently deform a chilled gas pipeline. Stresses of the magnitude observed during a single cycle would render a functioning pipeline inoperable.

1.2 Third Freeze Cycle: Overview

During this phase of the project, efforts were directed towards obtaining a better understanding of the heave characteristics of the soil and the pressures generated during freezing. New instrumentation for measuring total and differential soil heave and for measuring soil pressures during freezing was added.

The data have shown that significant amounts of heave occur in already frozen ground and that this is not confined to a thin layer near the freezing front. These observations are not accounted for in existing frost heave models.

The heave in already frozen soil is greatest when the freezing rate is slow and the temperature gradients small. Soil cores obtained at the end of the freeze cycle show that the amount and thickness of discrete ice lenses is greatest at depth within the profile.

Figure 1.1 Longitudinal section of trough

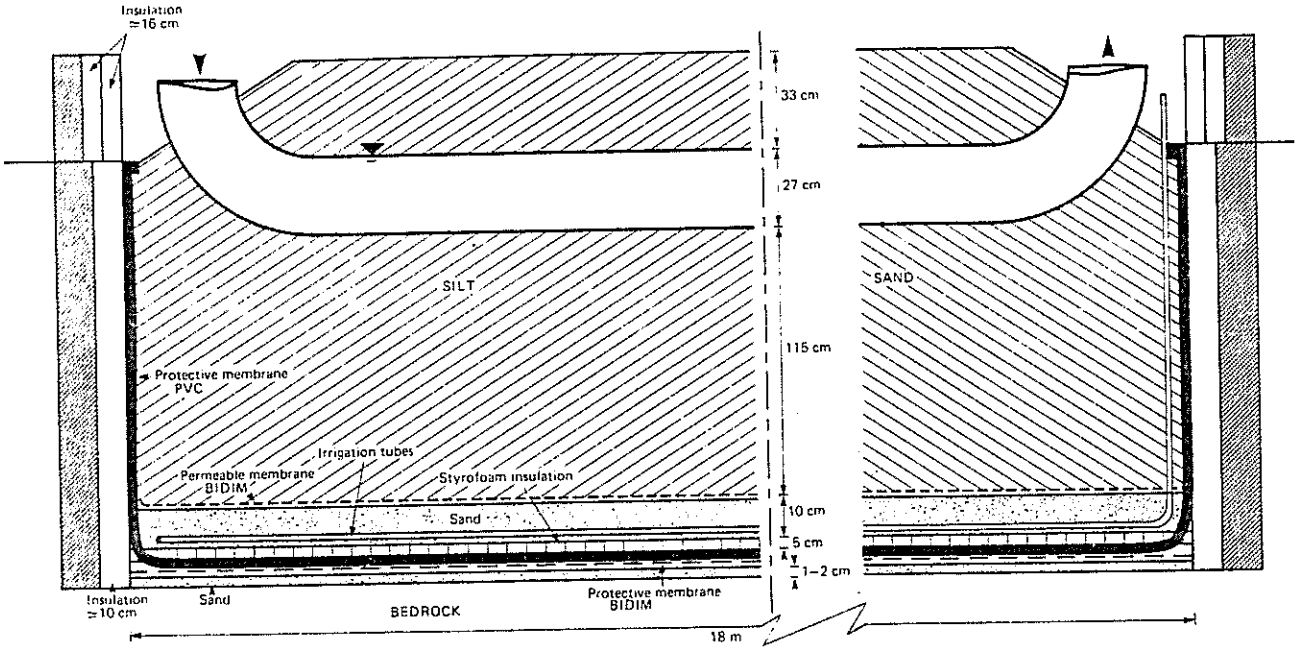
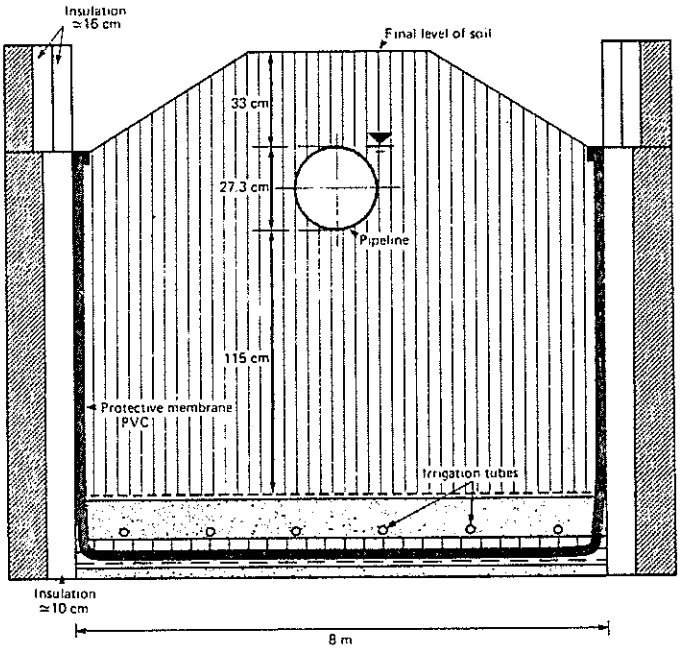


Figure 1.2 Cross-section of trough



II Experimental Design

2.1 General

Significant changes in instrumentation were made for the third freeze cycle in order to provide additional information on the soil freezing and frost heave processes. Specifically, an array of 10 magnet heave sensors and thermistor cables were installed in the silt to measure more accurately the rates and magnitude of heave and thermal change. Also, new instrumentation for determining soil stress was installed. For details, refer to the appropriate sections in this report.

2.2 Operating Conditions During the Third Freeze Cycle

The third freeze lasted 359 days from March 3, 1986 to February 25, 1987. Pipe temperature was maintained at -5.25 C and air temperature in the hall at -0.75 C. The thaw cycle was 84 days long commencing February 26, 1987 and ending May 21, 1987. During this period the cooling system for the pipe was switched off and the facility was maintained at 4 C. These thermal conditions during the freeze and thaw are similar to those of the second freeze cycle and will be maintained during the fourth freeze cycle which is anticipated to start early 1988. As in previous cycles, the water table was maintained at 30 cm beneath the pipe (90 cm beneath the soil surface).

During the third freeze cycle, there were several events which disrupted the air and pipe temperature for short periods of time. These events are recorded here since they are evident in some of the observations.

1. day 44 to 51 (April 16 to 23, 1986) malfunction of facility compressor.

2. day 81 (May 23, 1986) facility compressor off for a 15 hour period.

3. day 96 and 97 (June 7 to 9, 1986) both compressors broke down for 48 hour period, no significant changes were noted in the air temperature.

4. day 115 the compressor maintaining pipe temperature broke down for a 16 hours. The air temperature in the pipe reached a maximum of -0.85 C.

5. day 135 facility compressor off for 15 hour period, air temperature 2.8 C.

6. day 322 facility compressor off.

Table 2.1 outlines the timetable of events since the start of the project.

2.3 Description of Instrumentation and Observations

The thermal, hydrologic and heave characteristics of the soil are measured regularly. Information on pipe curvature and pipe stress are also gathered to examine the effects of frost heave on the pipe. Periodic measurements are made of soil density and moisture content. Earlier reports give a detailed description of the instrumentation and a summary of the frequency of readings (see Geotechnical Science Laboratories, 1982, 1983, 1984a, b, 1985).

2.4 Details of Re-instrumentation

Refurbishing and re-instrumentation took place during the latter part of January and early part of February 1986 following completion of the second thaw period. During this time all systems were checked and the refrigerator controls for both the atmosphere and pipe temperature were serviced.

Table 2.2 provides supplementary information on the new instrumentation and

Table 1.1 Timetable of Events

Event	Date		Operating Conditions	
	from	to	Air/Ground temp. (C)	Pipe temp. (C)
First Freeze	09/21/82	08/06/83	-0.75	-2.0
Surface Thaw	08/06/83	17/10/83	4.0	-2.0
Second Freeze	17/10/83	18/09/85	-0.75	-5.0
Second Thaw	18/09/85	01/02/86	4.0	ambient
Re-instru-mentation	01/02/86	03/03/86	-	-
Third Freeze	03/03/86	25/02/87	-0.75	-5.25
Third Thaw	25/02/87	21/05/87	4.0	ambient

Table 2.2 Frequency of Observations

Observation	Instrumentation	Frequency
soil temperature	thermocouple thermistor	daily every 3 days until day 217 then weekly
soil heave	telescoping heave rods magnetic heave sensors	weekly twice weekly until day 217 then weekly
surface heave	levelling	monthly
pipe heave	levelling	weekly
soil stress	Glotzl cells Petur cells	twice weekly twice weekly
pipe stress	strain gauges	twice weekly
phase composition/ water content	Time-domain reflectometry	weekly

Figure 2.1 shows the location of the new instrumentation installed for the third freeze period.

A series of thermistor cables and magnet rings were installed in two arrays, one parallel to the pipe (25 cm off axis) and the other normal to the pipe in the silt near section BB. These new temperature sensors give a better picture of the thermal regime in the silt.

Petur pressure cells, for measuring soil stress during freezing, were installed in four vertical profiles directly beneath the pipe in the silt section to augment the data obtained from the Glotzl cells. The Petur cells are physically smaller than the Glotzl cells and are constructed to obtain either total or directional pressure.

A brief review of the new instrumentation is presented in subsequent sections, for details see Patterson et al. (1986).

2.4.1 Thermal Regime

Sets of thermistor cables were installed in the soil at ten locations to augment the existing thermocouple sensors, as shown in Figure 2.1. The thermistors were installed in multiconductor cables at 0, 15, 30, 45, 60, 75, 90, 105, 120, 135 and 160 cm (+/- 2 mm). Once the cables were completed, each thermistor was calibrated to +/-0.05 C.

The cables were then placed in oil-filled access tubes in the facility so that the 0 cm thermistor was at the soil surface at the start of the third freeze cycle. The access tubes were optically surveyed on a regular basis to ensure that the position of each thermistor was known relative to the soil surface. Should the access tube heave at a different rate than the soil, then the position of each thermistor within the profile could be corrected.

The uncertainty in determining the position of the 0 C isotherm using thermistors is a function of the precision of calibration and how precicely the spacing between thermistors is known. For example, if a temperature gradient of 0.033 $^{\circ}C\ cm^{-1}$ (0.5 C over 15 cm) exists in the soil near the freezing front, the calculated position of the 0 C isotherm could be in error by +/- 1.5 cm if the uncertainty in thermistor calibration (+/-0.05C) is considered. As the temperature gradient becomes smaller, the error increases. For some sites, towards the end of the experiment, temperature gradients as low as 0.01 $^{\circ}C\ cm^{-1}$ were noted suggesting a possible uncertainty of +/- 5 cm in locating the 0 C isotherm. For this reason, temperature data are used to qualify the boundary between frozen and unfrozen soil.

2.4.2 Soil Heave

The use of magnet rings and a magnet sensor to measure soil heave has only recently been reported in the literature as an alternative to telescopic heave rods (Mackay, 1987). The principle of the apparatus has been used in geotechnical engineering for some time.

The apparatus used in this experiment is a refinement of the one described by Mackay (1987). It consists of three parts: a magnet ring; a magnet sensing device and a plastic access tube. The magnet ring is comprised of three small magnets installed in a plexiglass ring through which the access tube passes. The magnet sensing device consists of a piezoelectric detector, an aluminum rod which runs through a rack and pinion assembly and a digital readout. The piezoelectric detector is mounted at the end of the aluminum rod. As the sensor is lowered down the access tube by the rack and pinion assembly, an audible signal is generated when a magnet is encountered and the position within the soil profile is read on the digital readout.

The positions of magnet rings in a profile is determined with reference to a magnet ring on the soil surface (see Figure 2.2). The position of this ring is optically

Figure 2.1 Location of New Sensors

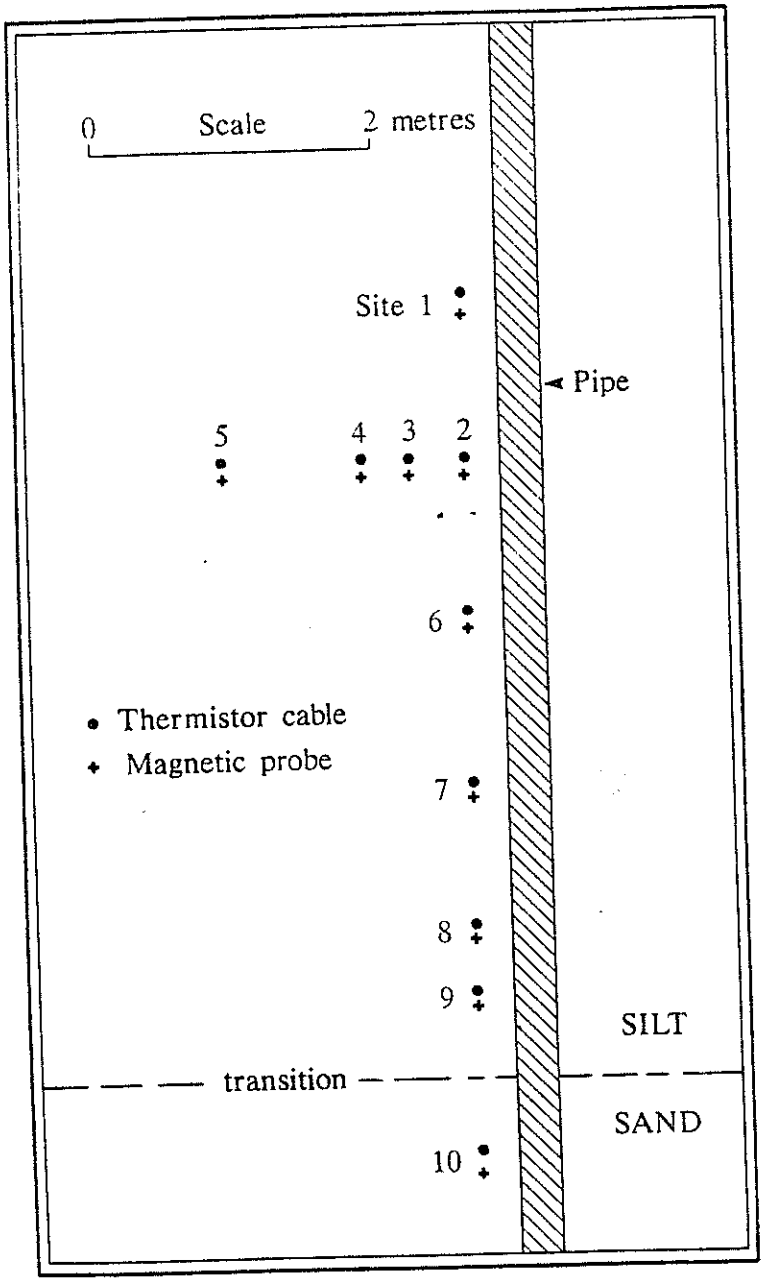
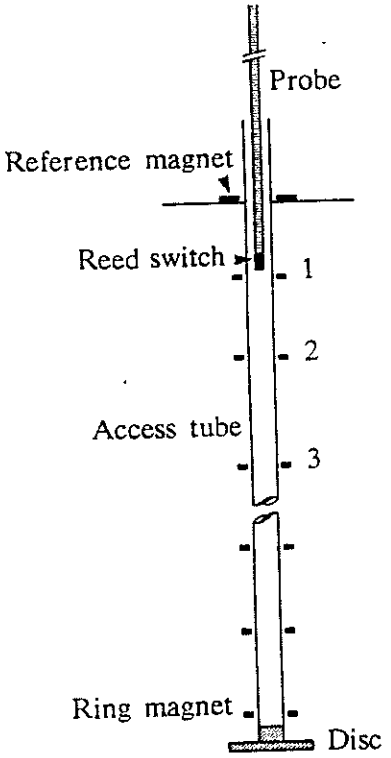


Figure 2.2 Magnet Heave Device



surveyed monthly to confirm the total heave at the site. In practice, the magnet sensor is lowered down the access tube until the surface ring is detected, the digital readout device is zeroed and the sensor is lowered until the depth to all successive rings is recorded.

The accuracy and reproducability of data obtained with this device is quite good since the digital readout is sensitive to within 0.1 mm. Test trials using different untrained operators have shown that magnet rings in a 1.4 m profile could be repeatedly located to within 0.2-0.3 mm. Part of this uncertainty is undoubtedly due to backlash in the rack and pinion assembly which is in the order 0.1-0.2 mm.

2.4.3 Soil Stress

A new array of soil pressure meters was installed to measure soil stress during freezing. Petur cells were used since they are physically smaller than Glotzl cells and can be configured to obtain total or directional pressure. The principle of operation for the Petur soil pressure system is the same as for the Glotzl cells. The same manometer and gas pressuring system is used for both Glotzl and Petur cells.

The Petur cells were installed in four vertical profiles under the pipe. Four cells to determine total pressure were installed at 20, 40, 60 and 80 cm below the pipe in each profile. In addition, two directional cells were installed, in two of the profiles, 40 cm beneath the pipe to monitor lateral and vertical pressures.

Laboratory testing of the Petur cells suggested that the system should operate satisfactorily. However, during the course of the freeze cycle, the Petur cells began to fail. After the freeze cycle was completed, the devices were removed and it was found that the rubber bulbs had deteriorated and a number had visible pin-holes causing oil leakage. Subsequently, a replacement bulb has been found which does not deteriorate so readily. These have been installed for the fourth freeze cycle.

Another aspect which was not examined previously is the temperature dependence of the Petur cells. Experiments carried out in Caen prior to refurbishing for the fourth freeze cycle suggested that a temperature dependence does exist. Given that the materials (rubber and oil) would experience contraction during cooling, it is not surprising that some temperature sensitivity would exist. This aspect is currently under investigation in Caen and in Ottawa to ensure that temperature sensitivity can be accounted for.

A new device will also be used during the fourth freeze cycle to obtain additional soil pressure information. This device consists of a strain gauge pressure transducer encapsulated in a golf ball-sized sphere. The transducer is connected to a battery operated radio frequency transmitter. As pressure is exerted on the sphere, the pressure can be determined by tuning into the sensor. The repetition rate of the transmitter varies with the pressure and the pulse width varies with the temperature. The advantage of this device is that it is less intrusive than the Petur and Glotzl cells, which have connecting cables and are disruptive elements within the soil.

III Observations, Third Freeze Cycle

3.1 General

The data and observations reported in this section cover the period March 3, 1986 (day 0) to February 25, 1987, (day 359).

3.2 Thermal Regime

The ten additional temperature profiles provided an improved picture of the thermal regime in the silt section adjacent to the pipe axis and at right angles to the pipe near section BB (see Figure 2.1). The temperature data establish the location of the freezing front and the range of temperatures and temperature gradients over which heave persists.

As indicated previously, the position of the access tubes is optically surveyed monthly during the course of the freeze cycle so that the true position of the thermistors is known. In the case of the thermistor cables located adjacent to the pipe (sites # 1, 2, 6, 7, 8, 9, and 10), there was essentially no difference between the surface heave and the heave of the access tubes. This indicates that the access tube was grasped by the freezing ground and heaved at the same rate as the soil surface, hence, the position of the thermistors with respect to the soil surface in those profiles remained constant during the freeze period. This is not surprising since the access tubes are located about 12 cm from the edge of the pipe (eg. 25 cm off pipe axis and the pipe is 273 mm in diameter) and the rapid lateral freezing during the early part of the experiment quickly froze the access tubes in place.

The heave of the access tubes for the thermistor cables located normal to the pipe axis (sites # 3, 4 and 5) was slower than that of the soil surface. Generally, the access tubes did not begin to heave until about 30 or 40 cm of soil was frozen. The position of the thermistors in these profile, with respect to the soil surface, changed with time and had to be accounted for when trying to determine the position of the 0 C isotherm.

Representative temperature data for thermistor string # 7 (located 2.1 m along the pipe axis in the silt section and 25 cm off the pipe axis) are shown in Figure 3.1. The temperature patterns shown this figure are typical of the thermistor strings located along the pipe axis. The bulge in the 25 to 55 cm zone reflects the presence of the pipe which is buried about 30 cm beneath the soil surface.

The position of the 0 C isotherm for site # 7 is shown in Figure 3.2. From day 0 to day 14 the soil froze laterally from the pipe and within a short period of time the first 60 cm or so of the access tube was frozen in place.

Figure 3.3 shows soil position of the 0 C isotherm parallel to the pipe axis (25 cm off axis) for selected dates. As expected, frost penetration is greatest in the sand section and in the silt within about two metres of the transition. The depth of frost penetration is relatively uniform for the thermistor strings located 2 to 6 m from the sand-silt transition (sites 1, 2, 6 and 7).

Figure 3.4 shows position of the 0 C isotherm normal to the pipe axis near the BB cross-section (located about 4.4 m from the sand-silt transition in the silt section) for selected dates. The penetration of the 0 C isotherm is greatest nearer the pipe and as one moves away from the pipe, the rate and depth of frost penetration is predominantly controlled by the ambient conditions in the facility (-0.75 C).

3.3 Hydrologic State

Water content data was obtained during the installation of the magnet

Figure 3.1 **Temperatures at Site 7 for Selected Dates**

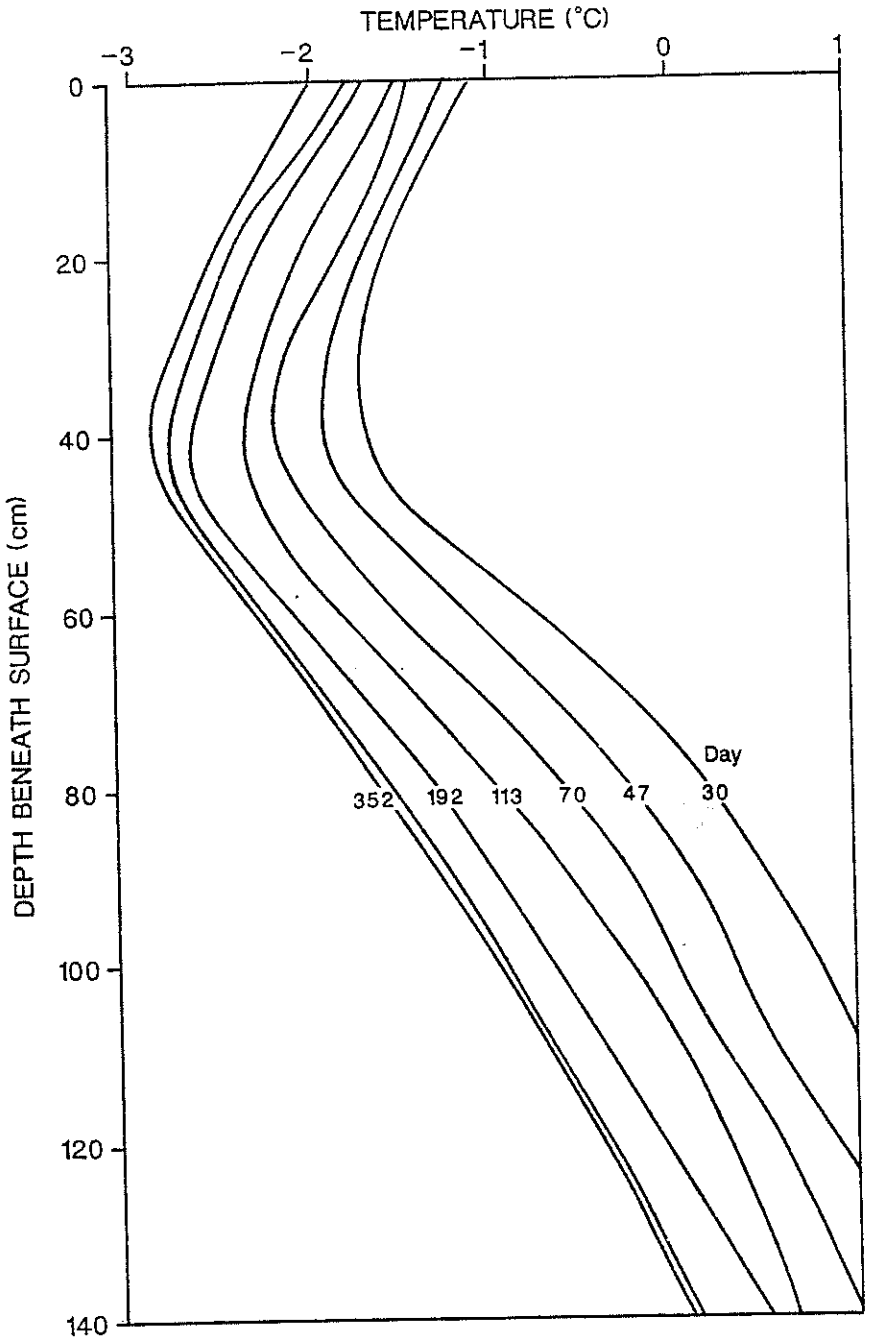


Figure 3.2 Position of the 0 C Isotherm at Site 7

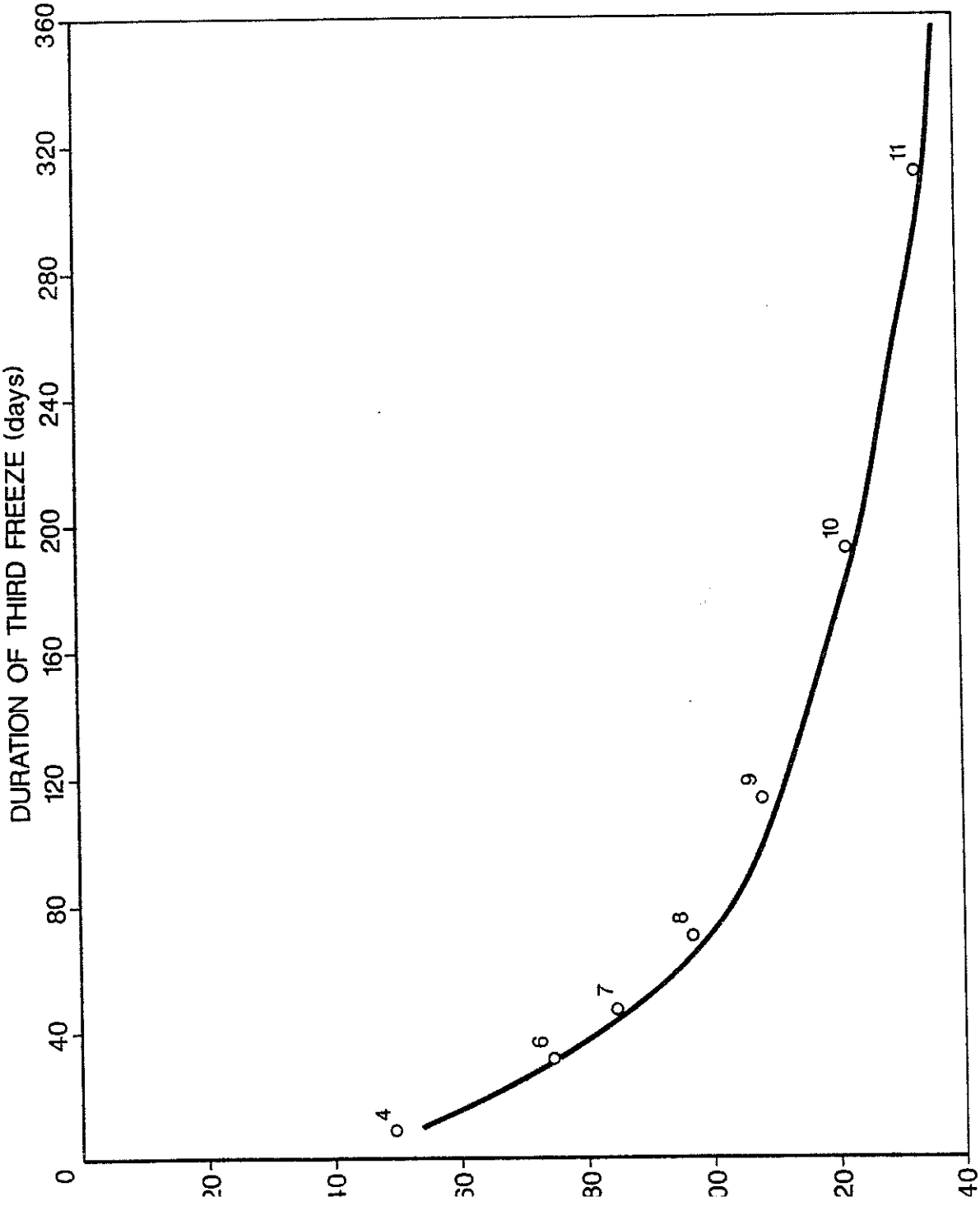


Figure 3.3 **Position of the 0 C Isotherm Parallel to the Pipe Axis in the Silt Section for Selected Dates**

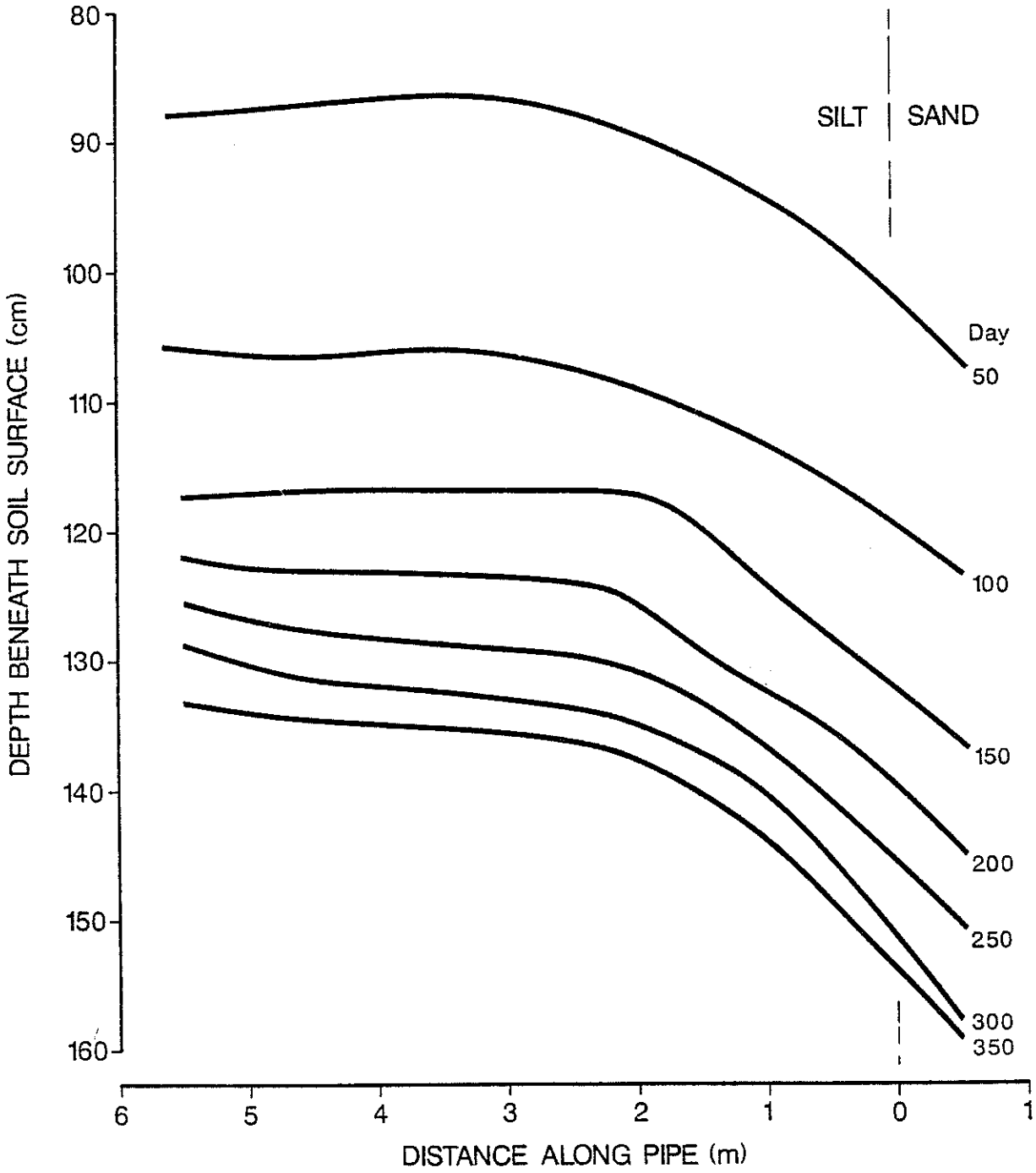
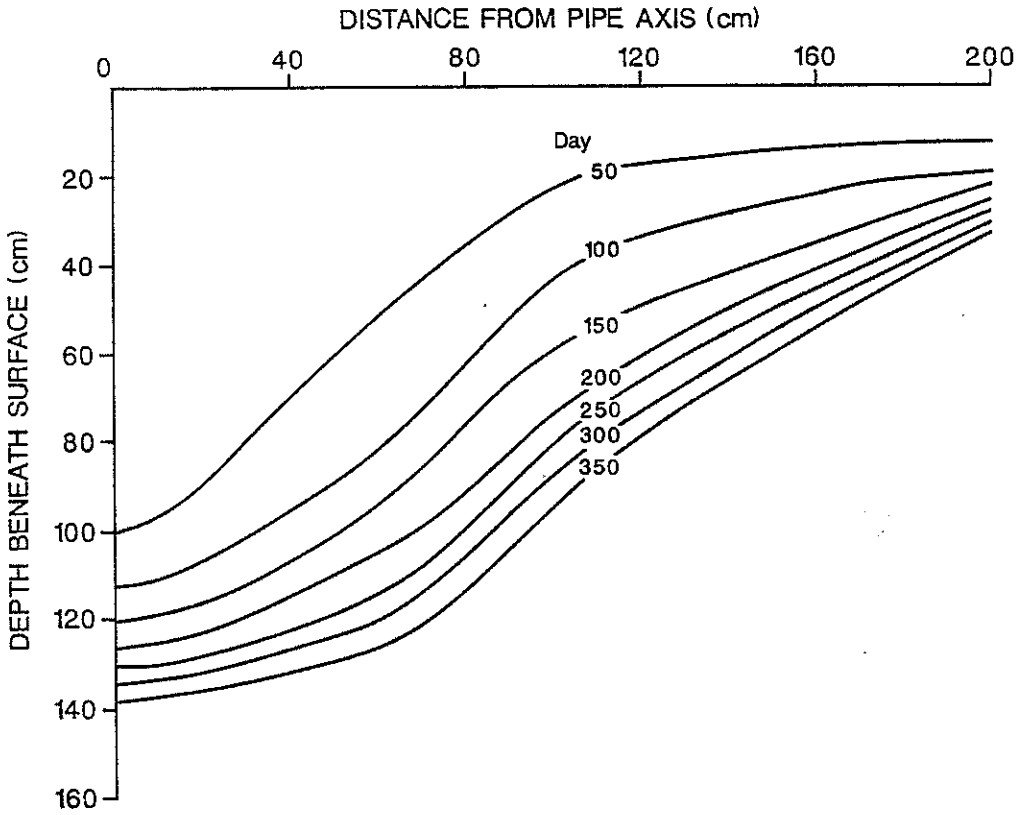


Figure 3.4 **Position of the 0 C Isotherm Normal to the Pipe Axis Near Cross-section BB for Selected Dates**



heave and thermistor access tubes at the end of the second thaw cycle. These data are summarized in Table 3.1.

Soil cores were obtained at the end of the third freeze for water content determination and preservation (using the resin impregnation technique). The values of water content and dry density plus phase composition information was used to determine the water/ice balance at two of the core sites. These data are discussed with respect to the accumulations of ice determined using the strain data. The results will be discussed in chapter 4.

3.4 Pipe Heave

Figure 3.5 shows the pipe shape for selected dates during the third freeze cycle. The curvature of the pipe is similar to that found during the other freeze cycles.

Figure 3.6 shows the net heave of the pipe on day 358 for both the second and third freeze cycle (net heave is the elevations on day 358 minus the position on day 0). The figure shows that the amount of heave in the silt section was up to 1.5 cm greater than that found during the second freeze cycle for the equivalent period of time. Also, the heave in the sand section during the third freeze was up to 1.4 cm less than that observed during the second freeze. Why the silt would experience more heave and the sand less is not completely understood considering the boundary conditions for both cycles were the same.

It should be noted that the position of the pipe on day 0 is different than it was at the start of the previous freeze cycles. The pipe has been slowly jacked upward in the soil profile by successive freeze-thaw cycles; as is shown in Figure 3.7.

3.5 Soil Heave

Soil heave is detected from four separate measurements:

1. pipe heave (section 3.4)
2. heave of the soil surface determined by optical levelling
3. soil heave determined by the telescopic heave rods
4. soil heave determined by the magnet heave device

Where possible, these data are correlated and reported in subsequent sections.

3.5.1 Surface Levelling

Figure 3.8 shows the topography of the soil surface determined by optical levelling at the end of the third freeze (day 358). The plan shows one half of the facility with the top edge of the diagram being the pipe axis. As has been noted in previous freeze cycles, the maximum surface movement occurs along the pipe axis in the central portion of the silt section. Heave decreases laterally from the pipe axis in the silt and decreases towards the sand-silt transition. In the area of the sand-silt transition, the contours become normal to the pipe axis. The depth and rate of frost penetration in the silt near the transition is much greater than areas more removed from this boundary. Soil heave is increasingly dominated by interstitial freezing with a reduced amount associated with water migration.

3.5.2 Magnetic Heave Devices

Figure 3.9 shows the total heave at sites 2, 3, and 4 which are perpindicular to the pipe axis near cross-section BB. The symbols represent heave values determined by optical levelling. The agreement between the two methods is generally quite good. As expected, the total heave decreases the further the site is from the pipe (site 2 is located 25 cm from the pipe; site 3 and 4 are 65 cm and 100 cm respectively).

Table 3.1 Gravimetric Water Contents at Various Sites in the Silt Section

Site Number

Depth (cm)	6	7	8	9	10
0 - 20	14.7	17.4	18.0	19.1	4.4
20 - 40	20.3	20.9	20.5	20.0	4.7
40 - 60	21.4	22.3	21.0	20.1	5.4
60 - 80	32.2	22.7	22.0	21.6	8.5
80 - 100	24.2	23.7	23.6	22.1	13.1
100 - 120	22.1	21.9	23.1	21.0	14.5
120 - 140	20.9	21.8	19.7	18.5	15.8
140 - 160	19.2			18.5	

Depth (cm)	3	4	5
0 - 20	17.5	18.1	19.1
20 - 40	19.1	19.1	20.6
40 - 60	20.6	26.8	20.3
60 - 80	21.3	20.1	18.6
80 - 100	20.7	21.6	20.7
100 - 120	21.5	20.9	21.0
120 - 140	21.2	21.0	21.8
140 - 160	20.5	17.2	18.9

Site #	Distance in m from Pipe	Transition
3	0.65	4.40
4	1.00	4.40
5	2.00	4.40
6	0.25	3.32 in silt
7	0.25	2.09
8	0.25	1.11
9	0.25	0.63
10	0.25	0.69 in sand

Figure 3.5 Pipe Shape During the Third Freeze

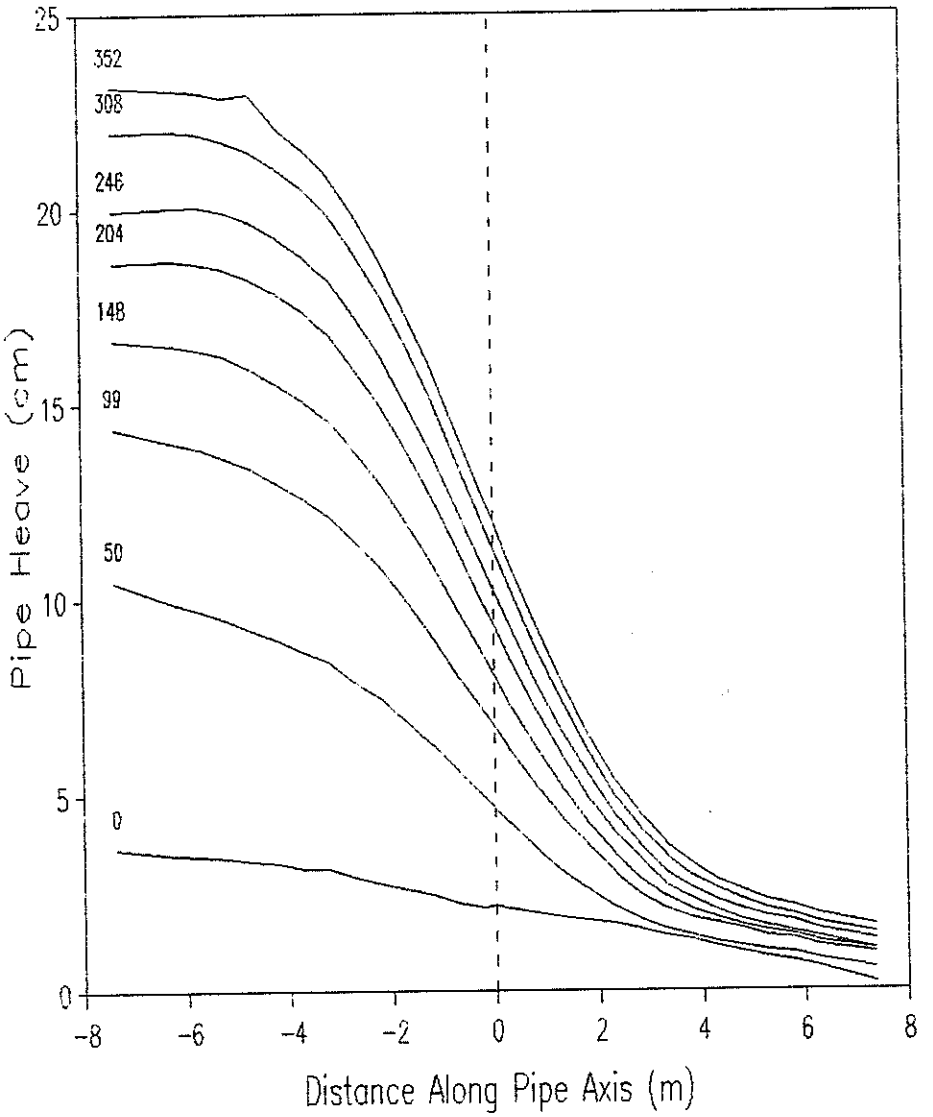


Figure 3.6 Pipe Heave on Day 358 for the Second and Third Freeze Cycles

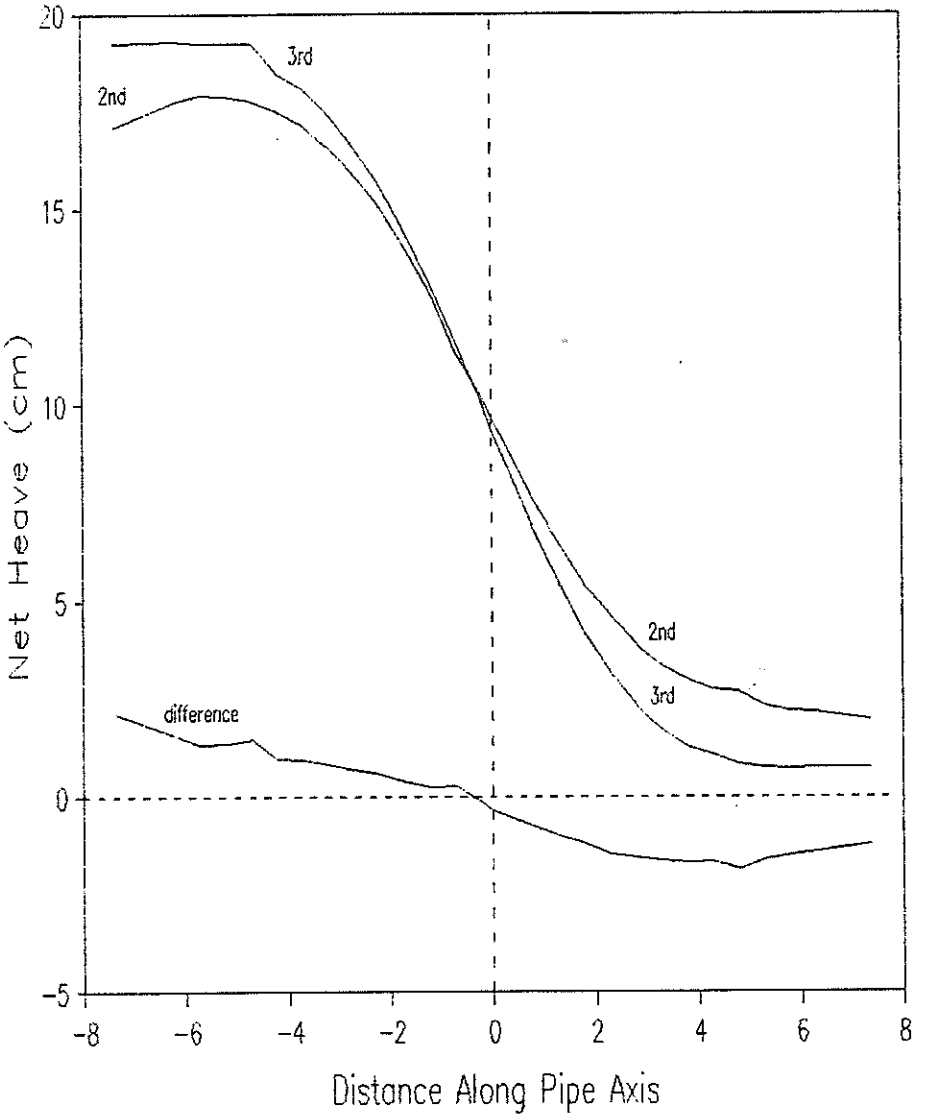


Figure 3.7 Pipe Shape at the Start of the Freeze Cycles

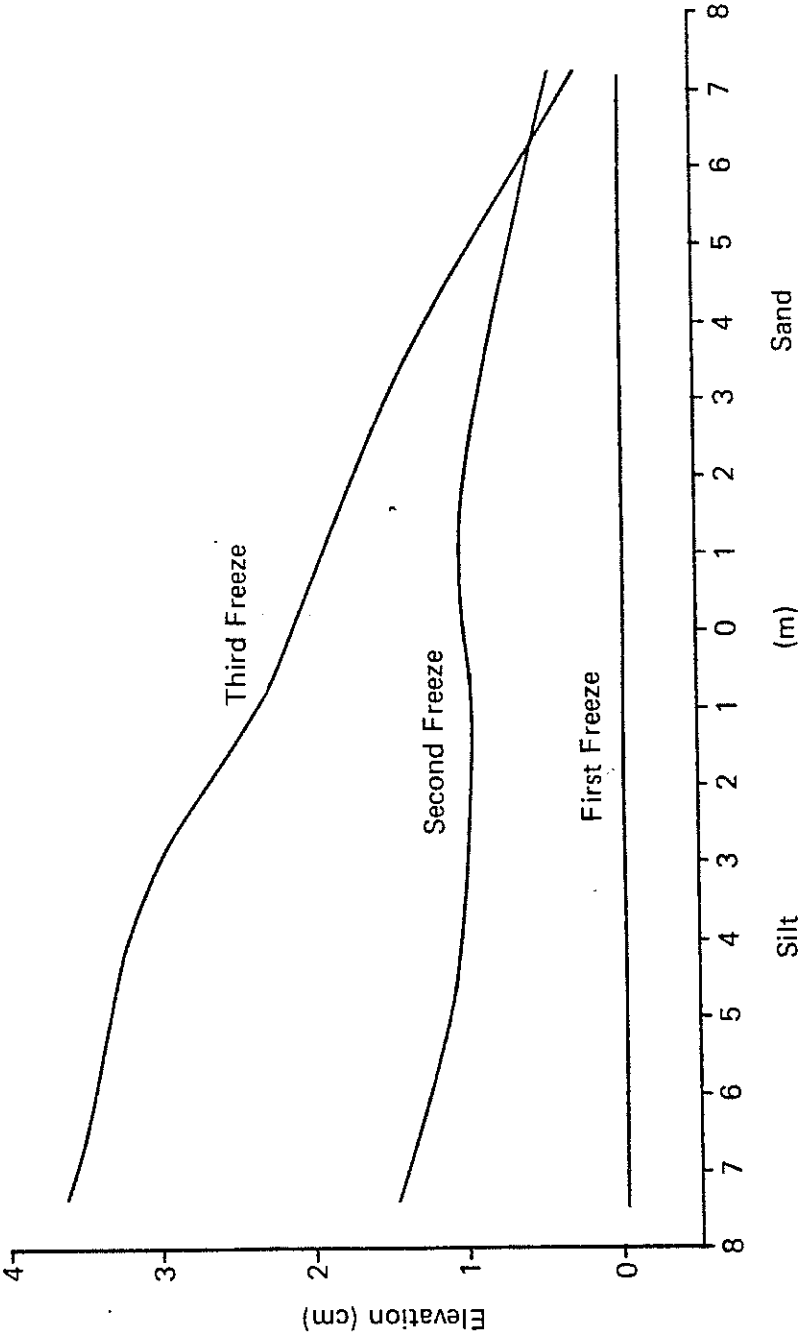


Figure 3.8 Surface Heave on Day 358 of the Third Freeze

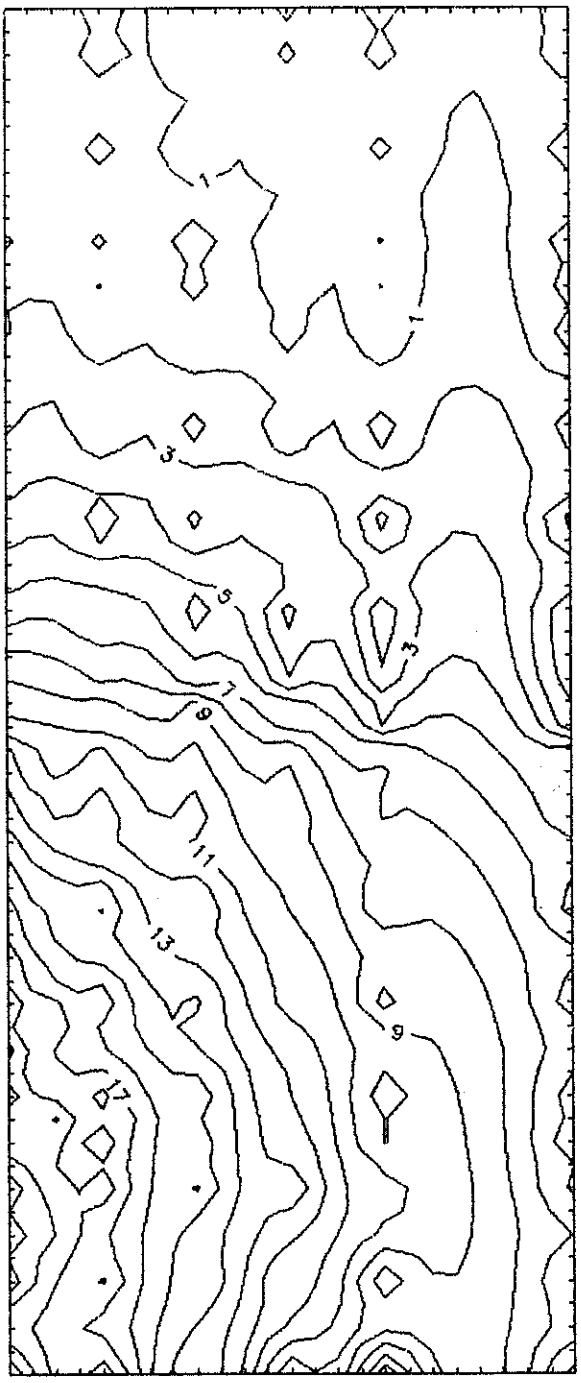
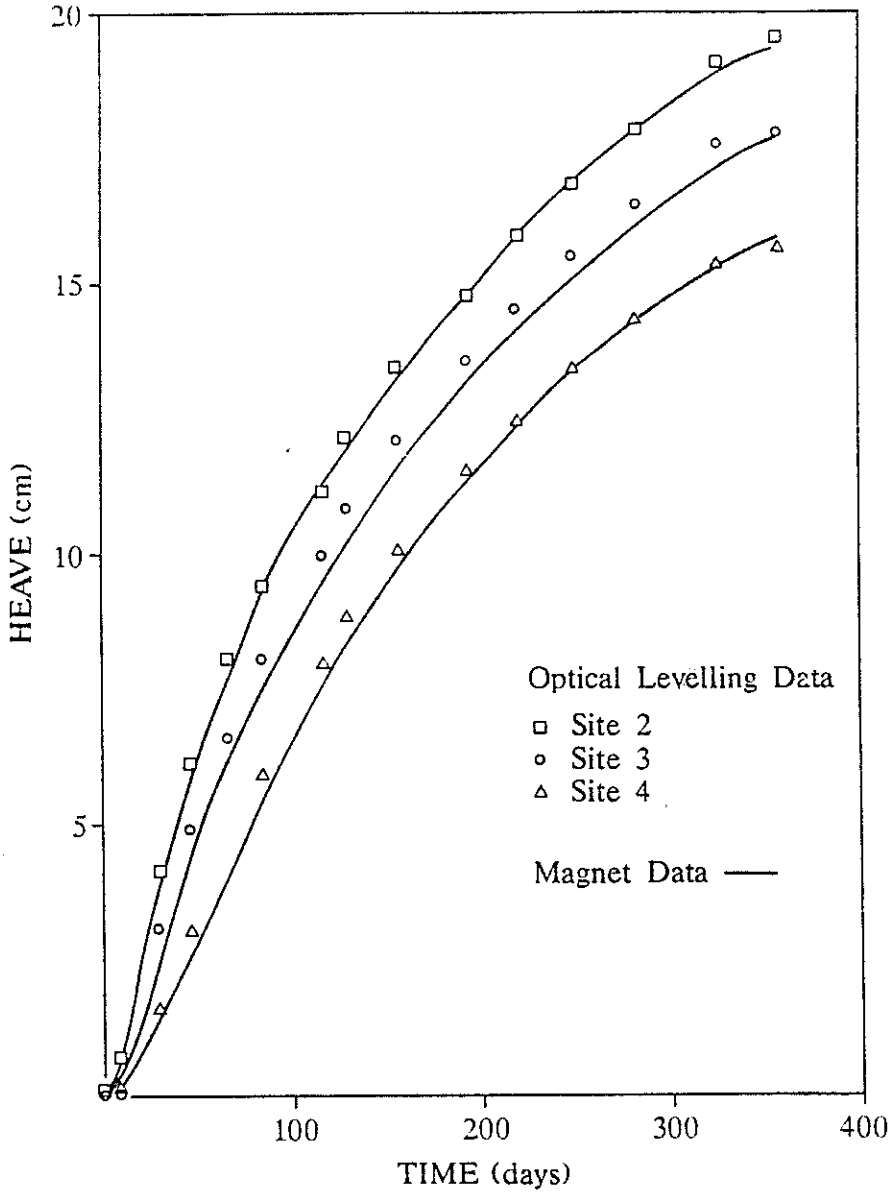


Figure 3.9 Total Heave Perpendicular to the Pipe Axis, from Magnet Heave Device



3.5.3 Telescoping Heave Rods

The total heave beneath the pipe in the silt section (3.92 m from the sand/silt transition) is obtained from a set of telescopic heave rods. This site is located close to magnet heave site # 2 (4.29 m from sand/silt transition and 27 cm off pipe axis). Another set of telescopic heave rods is located at 3.45 m from the sand/silt transition and about 20 cm off the pipe axis. This site is located close to the magnet heave site # 6 (3.18 m from sand/silt transition and 25 cm off pipe axis).

The total heave for both sites is shown in Figure 3.10. The total heave recorded for the telescoping heave rod set which passes through the pipe axis was 18.8 cm which is comparable to the 19.4 cm recorded at magnet heave site 2. The heave at the site beside the pipe was 17.2 cm which agrees closely with the 17.6 cm measured at magnet heave site # 6.

A comparison of the heave characteristics for the sites beside the pipe axis will be made in chapter 4.

3.6 Differential Strain in the Caen Silt

3.6.1 General

Most of the observed heave in the silt section cannot be accounted for by the freezing of interstitial water. In fact, only 0.032 cm of heave would occur for every centimeter of soil frozen (based on an average volumetric water content of 0.35 $cm^3 cm^{-3}$ and assuming all water freezes just below 0 °C). This is much less than was observed. For example, on day 358 the position of the 0 °C isotherm beside the pipe near the BB cross-section was 134 cm and the average heave was 18.5 cm (average of sites 1, 2 and 6). If interstitial freezing was dominant, about 4.3 cm of heave would have been detected. The remaining 14.2 cm must have been due to the water migration phenomenon.

If the temperature dependent phase composition of the silt is considered, then less heave could be ascribed to interstitial freezing. The average unfrozen water content of the silt in the -0.2 to -3.0 C temperature range is about 0.10 $cm^3 cm^{-3}$, hence, only 2.9 cm of heave could be ascribed to interstitial freezing leaving 15.6 cm of heave due to water migration.

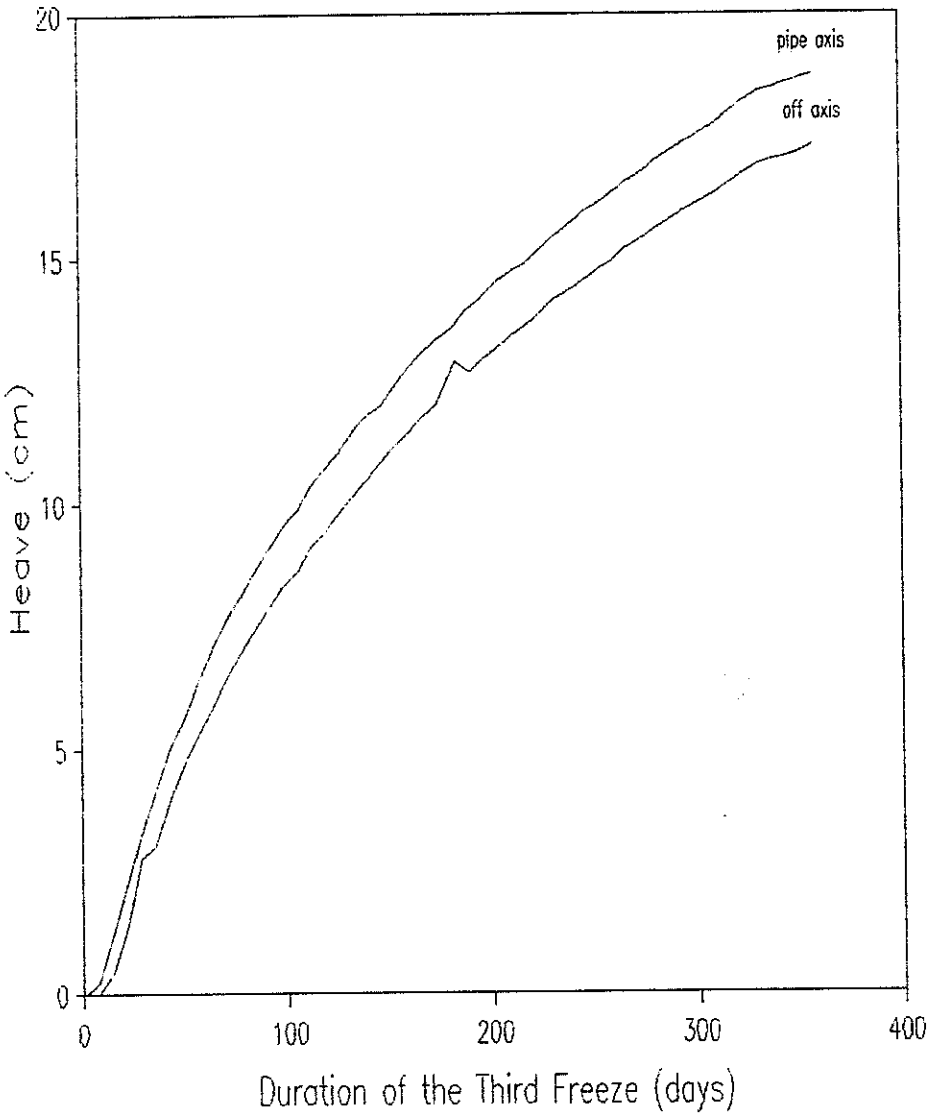
Existing frost heave models show that water will indeed migrate to the freezing front resulting in amounts of heave which are greater than can be attributed to interstitial freezing. Most views of the heaving process, however, regard heave as confined to a relatively small zone around the freezing front with little or no heave occuring in already frozen ground.

Quantifying the rates and magnitude of water migration to the freezing front is important area of study since it will permit characterization of the short term heave process for a soil. The generally accepted approach to obtain this data is by frost heave testing in the laboratory using small specimens under steep temperature gradients.

In nature, though, temperature gradients of several hundredths of a degree per centimeter are not uncommon and a substantial thickness of soil may be at temperatures close to the ice point. If the soil is fine-grained, it will contain a lot of unfrozen water and the material will be relatively permeable. Perhaps then, determining the rate and magnitude of heave in already frozen ground is of greater importance since this, in the long term, will ultimately dominate the total displacement observed in a frozen soil layer.

With this in mind, differential heave in the soil was examined using the data obtained from the magnet heave device and the telescoping heave rods.

Figure 3.10 Total Heave at Telescoping Heave Rod Sites in the Silt



3.6.1 Observations from Magnet Heave Data

Figures 3.11 to 3.13 show the observed strain for various soil layers at sites 2, 3 and 4; these being the sites perpendicular to the pipe axis near the BB cross-section. The heave data was expressed as strain (heave in layer relative to original thickness) to account for differences in soil layer thickness. The positions of the magnets at the start and end of the experiment for each layer and site are given in Table 3.2. The surface magnet at site 4 was disturbed because of repairs made to the access tube. No estimates of strain were possible in the uppermost soil layer after day 162.

These figures indicate that the amount of strain increases and the strain rate decreases the deeper the layer is within the profile. This reflects the fact that the rate of freezing and frost penetration decreased over time.

At the start of the freeze cycle, freezing was quite rapid and water could not migrate at a sufficient rate to create large, continuous ice lenses. Some ice enrichment did occur but appeared in the form of very small closely spaced hair-like lenses (core recovery at the end of the freeze cycle substantiates this, see chapter 4). As freezing continued, the freezing rate decreased, the temperature gradients were smaller and the magnitude of the strain increased. The slower rate of freezing permitted more water to migrate to the freezing front and within the frozen zone. Larger more continuous lenses formed as seen in soil cores taken at the end of the experiment.

The figures also show that heave in a soil layer continues after it is completely frozen through. This aspect is evidenced by examining the dates when a previously unfrozen layer starts to heave and observing the strain in the layer above (already frozen). In fact, at the end of the freeze cycle, there are five soil layers at site 4, totaling 59 cm in thickness, heaving at the same time (see Figure 3.13). These findings is discussed in more detail in chapter 4.

3.6.2 Observations from Telescoping Heave Rods

The differential strain at these sites is shown in Figures 3.14 and 3.15. Figure 3.14 is for the telescoping heave rods which pass through the pipe at 3.92 m from the sand-silt transition while Figure 3.15 is for the site adjacent to the pipe at 3.45 m from the transition. The depth beneath the soil surface for the numbered layers in these figures is found in Table 3.3 for the start and end of the freeze cycle.

The strain patterns shown are comparable in form to those obtained at the magnet heave sites. The data for the telescoping heave rod through the pipe does indicate that there was some instrumental difficulties. This set of telescoping rods does not have a ring attached to the end of the rod (a foot) as does the set adjacent to the pipe. On Figure 3.14, it appears that the 93.0 to 102.8 cm layer as well as the 102.8 to 113.5 layer began to heave on about day 128. This suggests that the two telescoping rods associated with these soil layers were binding together, hence, as the upper most soil layer began to heave, the lower rod was also pulled up. The irregular pattern of strain for the 102.8 to 113.5 cm layer between days 128 and day 200 shows this quite clearly. Also, the strain in the 93.0 to 102.8 cm layer is less than expected and may be due to the inability of the rod to move freely.

The telescoping heave rods adjacent to the pipe (Figure 3.15) have feet attached to the end of the rods and binding of rods would be less likely to pull up a rod from beneath when the one immediately above begins to move.

The strain pattern for the site immediately adjacent to the pipe is in close proximity to magnet heave site 6. A comparison of observations will be made in chapter 4.

Figure 3.11 Strain at Magnet Heave Site 2

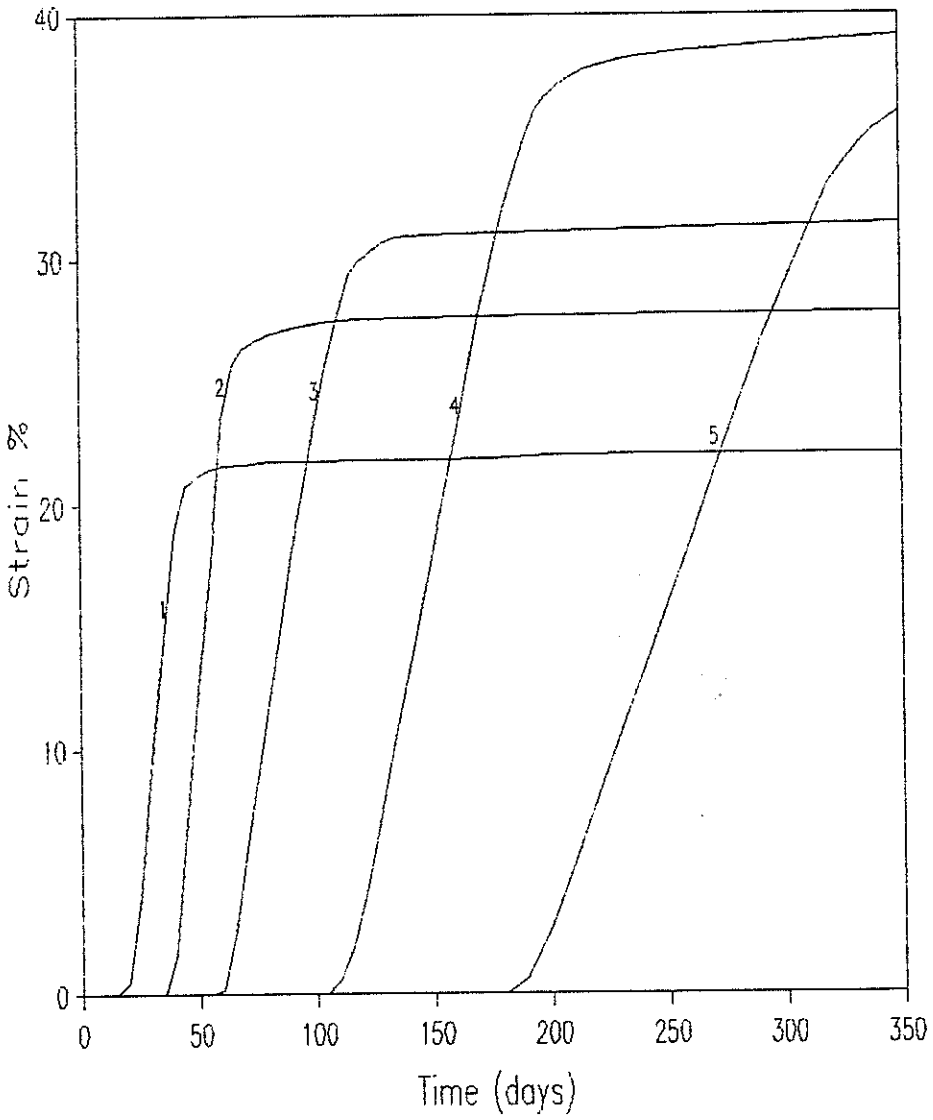


Figure 3.12 Strain at Magnet Heave Site 3

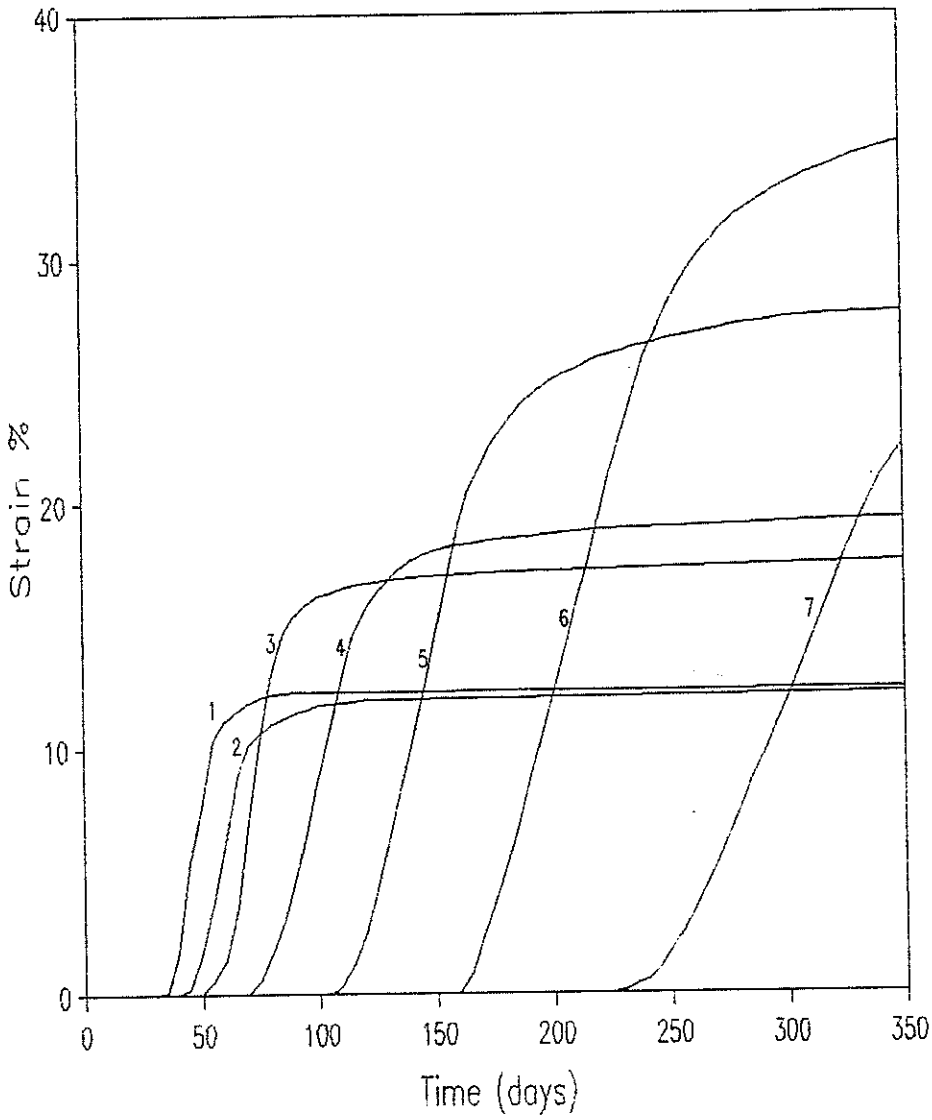


Figure 3.13 Strain at Magnet Heave Site 4

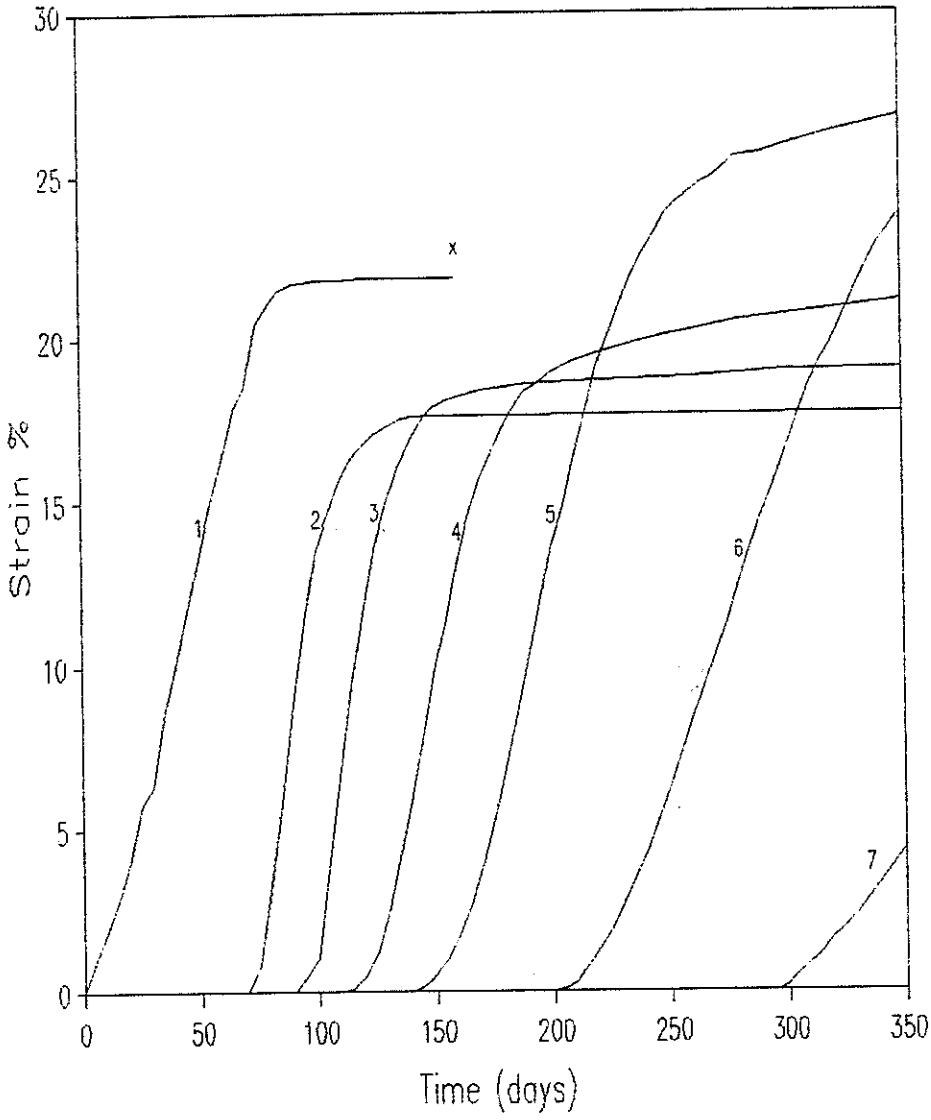


Table 3.2 Positions of Magnets (cm) at the Start and End of the Experiment

	Layer	Day 0	Day 357
Site # 2	1	61.4 - 72.7	64.4 - 78.1
	2	72.7 - 81.2	78.1 - 89.1
	3	81.2 - 93.0	89.1 - 104.5
	4	93.0 - 102.8	104.5 - 118.1
	5	102.8 - 113.5	118.1 - 132.6
Site # 3	1	30.1 - 41.0	33.2 - 45.5
	2	41.0 - 51.2	45.5 - 57.0
	3	51.2 - 59.5	57.0 - 66.7
	4	59.5 - 72.6	66.7 - 82.4
	5	72.6 - 82.4	82.4 - 94.9
	6	82.4 - 90.4	94.9 - 105.8
	7	90.4 - 99.6	105.8 - 117.0
Site # 4	1	0.0 - 21.2	
	2	21.2 - 30.6	25.1 - 36.2
	3	30.6 - 41.4	36.2 - 48.9
	4	41.4 - 51.2	48.9 - 60.6
	5	51.2 - 60.2	60.6 - 72.0
	6	60.2 - 70.8	72.0 - 85.1
	7	70.8 - 80.4	85.1 - 95.1

Figure 3.14 Strain at Telescoping Heave Rod Site Through the Pipe Axis in the Silt

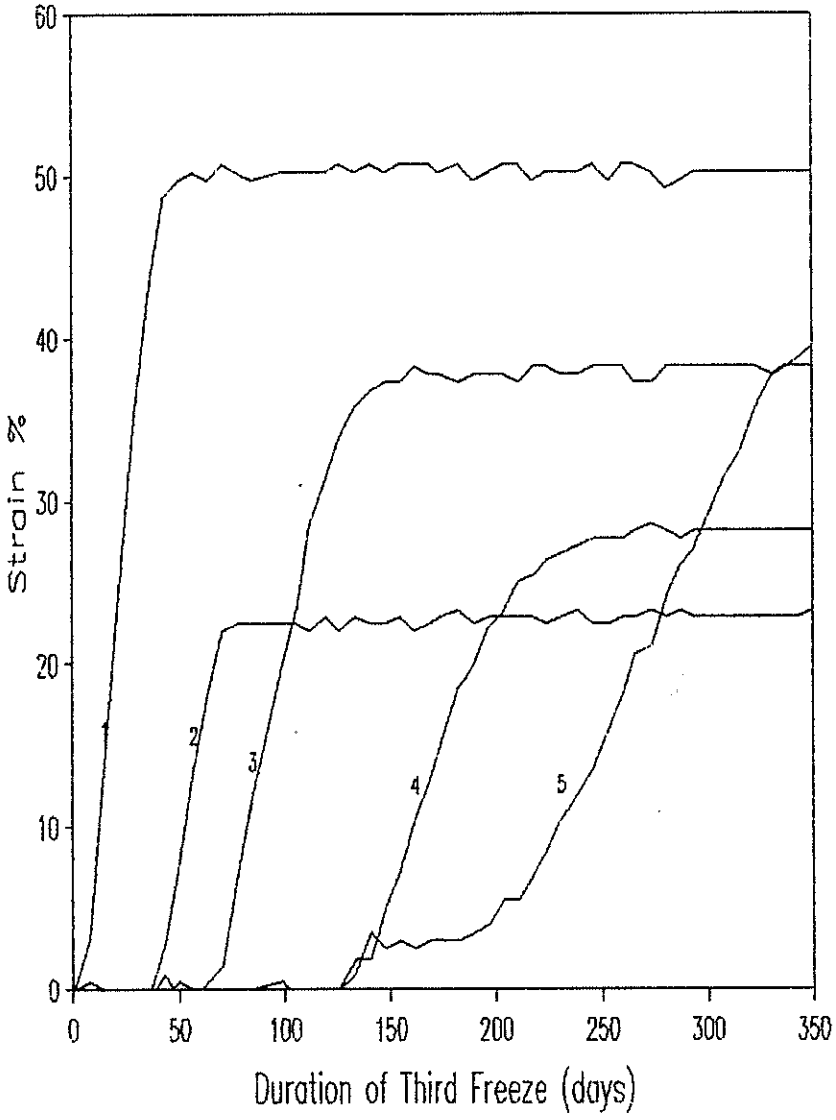


Figure 3.15 **Strain at Telescoping Heave Rod Site Adjacent to the Pipe Near Cross-section BB**

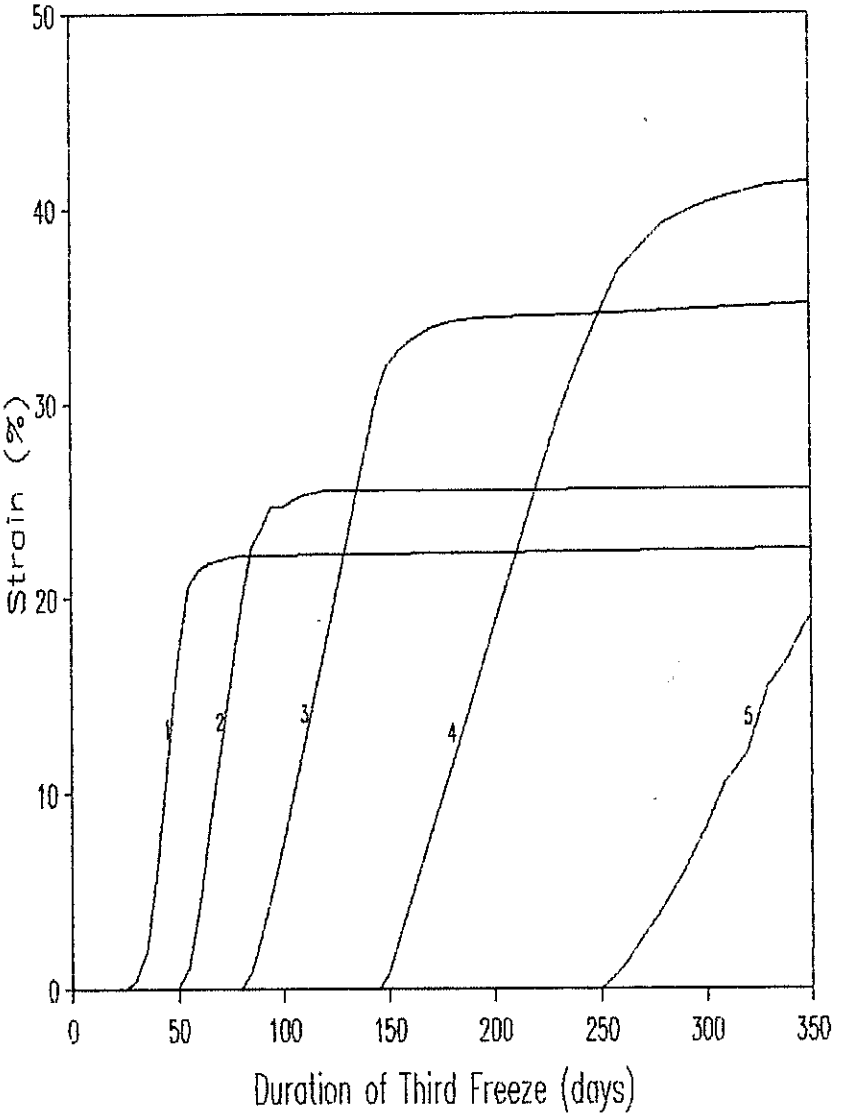


Table 3.3 Positions of Telescoping Heave Rods at the Start and End of the Experiment

	Layer	Day 0	Day 357
Through pipe at 3.92 m from sand-silt transition	1	61.4 - 72.8	64.4 - 78.1
	2	72.8 - 81.3	78.1 - 89.0
	3	81.3 - 93.0	89.0 - 104.4
	4	93.0 - 102.8	104.4 - 118.0
	5	102.8 - 113.5	118.0 - 132.6
Beside pipe at 3.45 m from sand-silt transition	1	74.5 - 84.7	77.5 - 90.5
	2	84.7 - 94.7	90.5 - 102.6
	3	94.7 - 104.8	102.6 - 116.2
	4	104.8 - 114.8	116.2 - 130.2
	5	114.8 - 125.2	130.2 - 142.5

3.7 Stress in the Ground

3.7.1 Observations from Petur Cells

As noted previously, over half the Petur cells failed to operate properly. When the cells were recovered after the third thaw, pinholes were found in many of the bulbs. For many cells, the recorded pressures remained constant until the freezing front advanced towards the cell position, then recorded pressures dropped significantly. Perhaps the pressure exerted by the freezing soil was sufficient to cause oil to leak out of the cell into voids or into the soil water. After this initial drop in pressure, some of the cells began to indicate pressure changes when the freezing front reached the cell; others did not. In the first case, it appears that even though the bulb leaked oil, enough remained in and around the bulb that a pressure increase could be detected and sustained.

Figures 3.16 and 3.17 show the soil pressure values obtained using the Petur cells under the pipe in the silt section at 2.7 and 0.85 m from the transition respectively. The trends in pressure discussed previously are evident in these figures, however, the values obtained should be used only as a guide to the pressure state.

Figure 3.18 shows the values obtained at 100 cm from the surface in the silt section at 0.85 m from the transition. Three different cells were installed at this location. These cells are constructed so that the rubber bulb is either completely exposed (total pressure) or only partially exposed (directional) to the surrounding soil. One measures total pressure (omnidirectional); one measures mainly the vertical component (pressure exerted downward) and the third detects lateral pressures (pressures acting from one side).

The cell detecting total pressure began to indicate pressure changes on about day 90 after an initial pressure drop (leaking bulb). The cell detecting vertical pressure begins to change in a similar fashion. The cell detecting lateral pressure begins to change around day 105 and increases rapidly over the next 50 or so days. On day 100 the cells are about 107.5 cm beneath the soil surface and the freezing front is in this vicinity (position of cell and freezing front are referenced to magnet heave and temperature site # 8). In principle, it should be possible to examine the various components of the total pressure and to examine their evolution over time. The redesign undertaken for the fourth freeze cycle will, it is hoped, allow us to measure this in detail.

3.7.2 Observations from Glotzl Cells

Figure 3.19 shows the pressures recorded at the 'BB' transition near the middle of the silt section. The depths of each cell as noted on the figure refer to their initial placement beneath the pipe before the first freeze. The exact position before this freeze was not known. Also, their true position within the profile changes as freezing and heaving progress.

A rise in recorded pressure for the guages indicates that the cell is frozen in. The Glotzl cell at 10 cm showed a general rise in pressure from the start of freeze until about day 150; the other gauges at 46 and 86 cm remained relatively unchanged. After day 150, the 10 cm cell began to indicate a gradual reduction in pressure levels suggesting that there was a relaxation of the frozen material associated with continuing deformation. The cell initially at 46 cm beneath the pipe began to freeze in on about day 215 and never really showed any substantial pressure levels for the rest of the freeze cycle.

The sudden drop in the pressure for the 10 cm cell recorded for days 96 to 103 occurred during a breakdown of the compressors which lasted from day 96 to day 98.

Figure 3.20 shows the pressures recorded at the "AA" transition near the middle of the sand section. The pressures

Figure 3.16 **Soil Pressures in the Silt from Petur Cells: 2.7 m from the Sand-silt Transition**

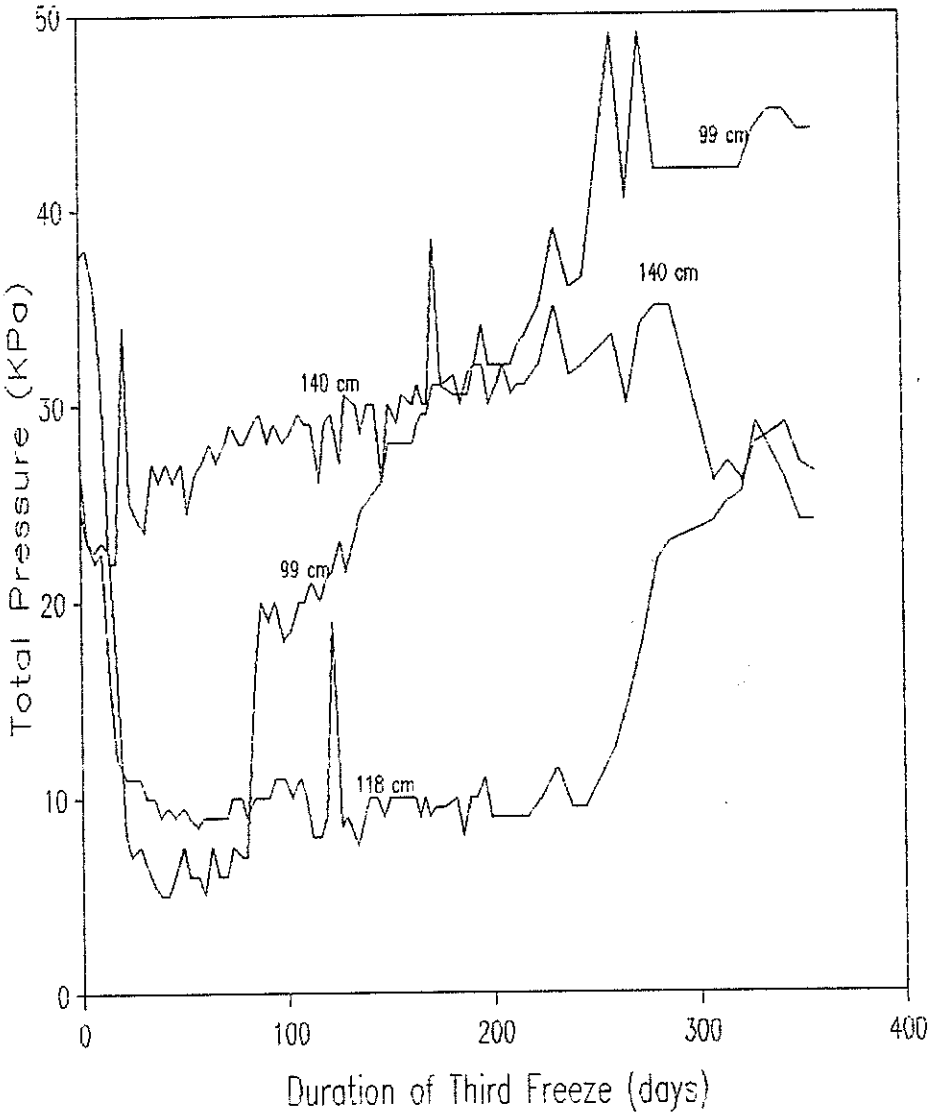


Figure 3.17 **Soil Pressures in the Silt from Petur Cells: 0.85 m from the Sand-silt Transition**

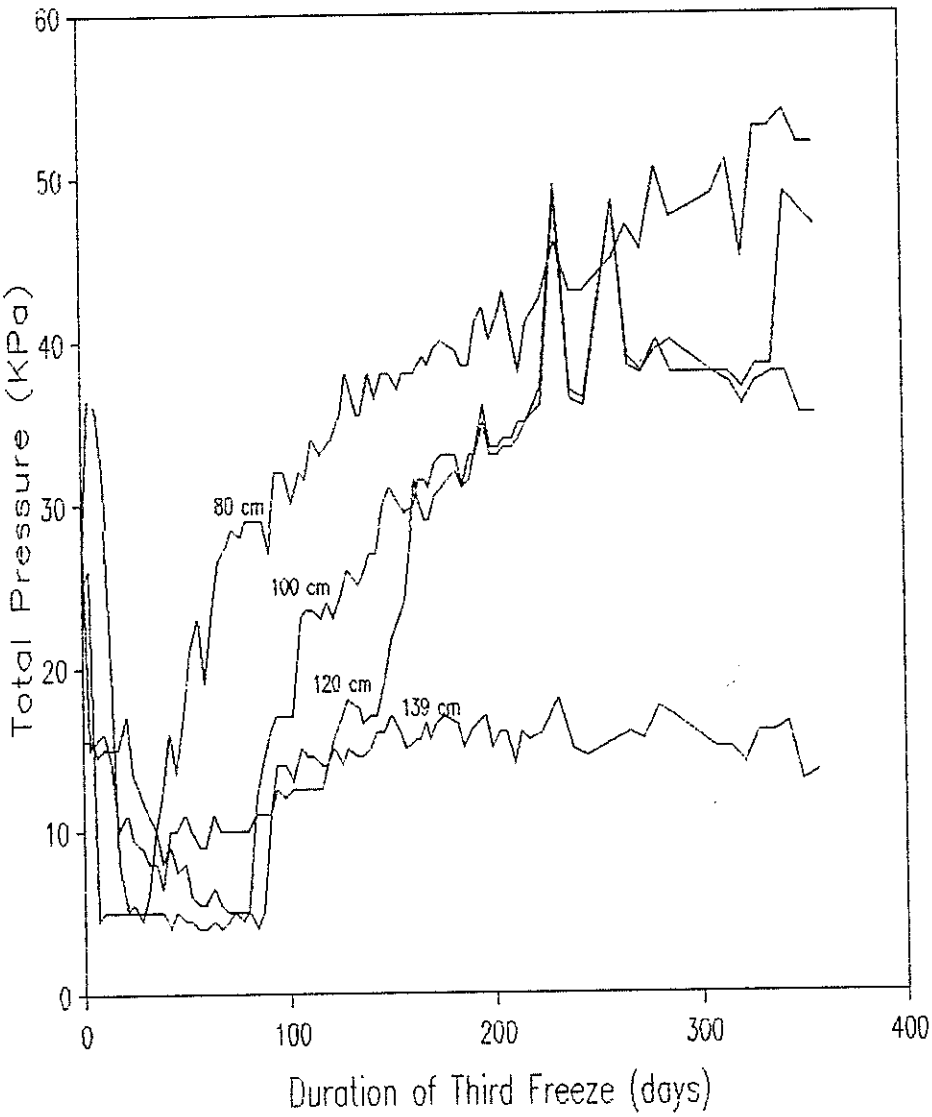


Figure 3.18 **Total and Directional Pressures in the Silt at 100 cm, 0.85 m from the Sand-silt Transition**

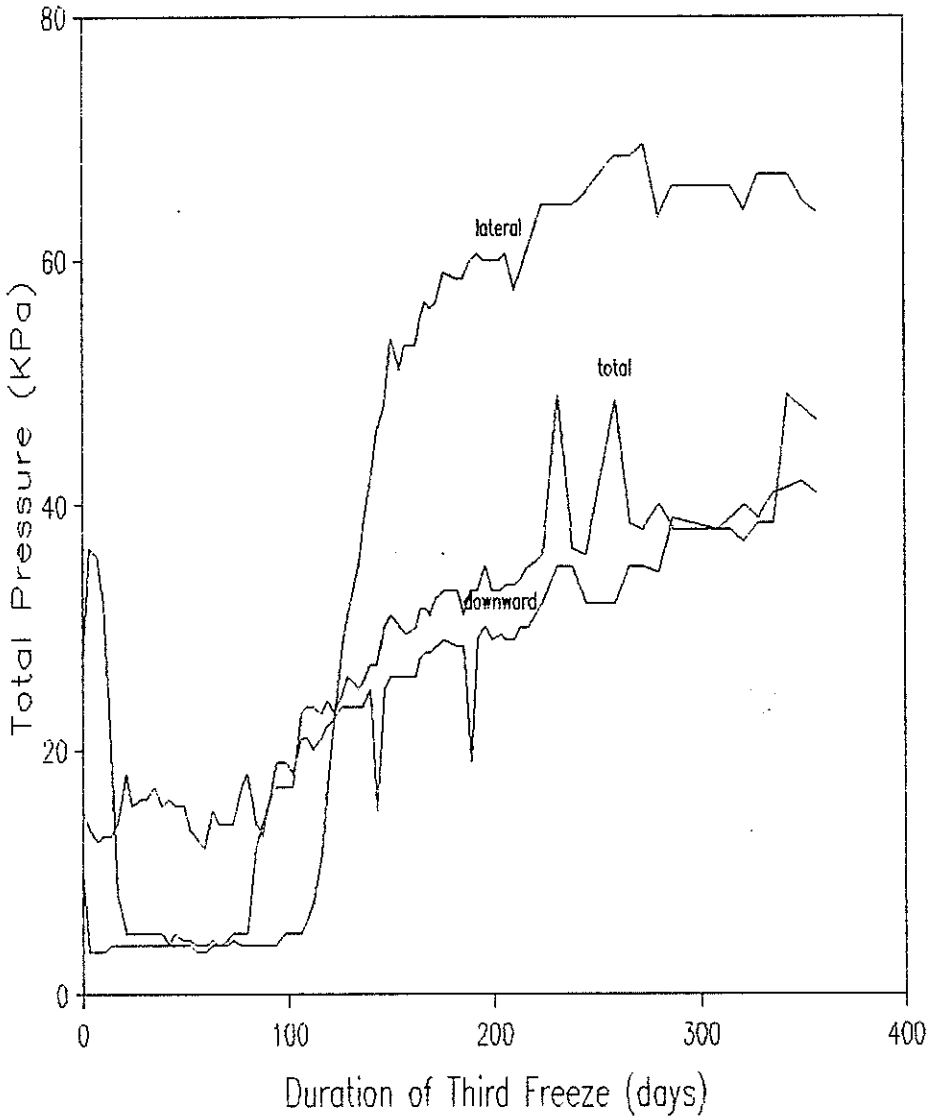


Figure 3.19 Soil Pressures from Glotzl Cells in the Silt Near the BB Cross-section

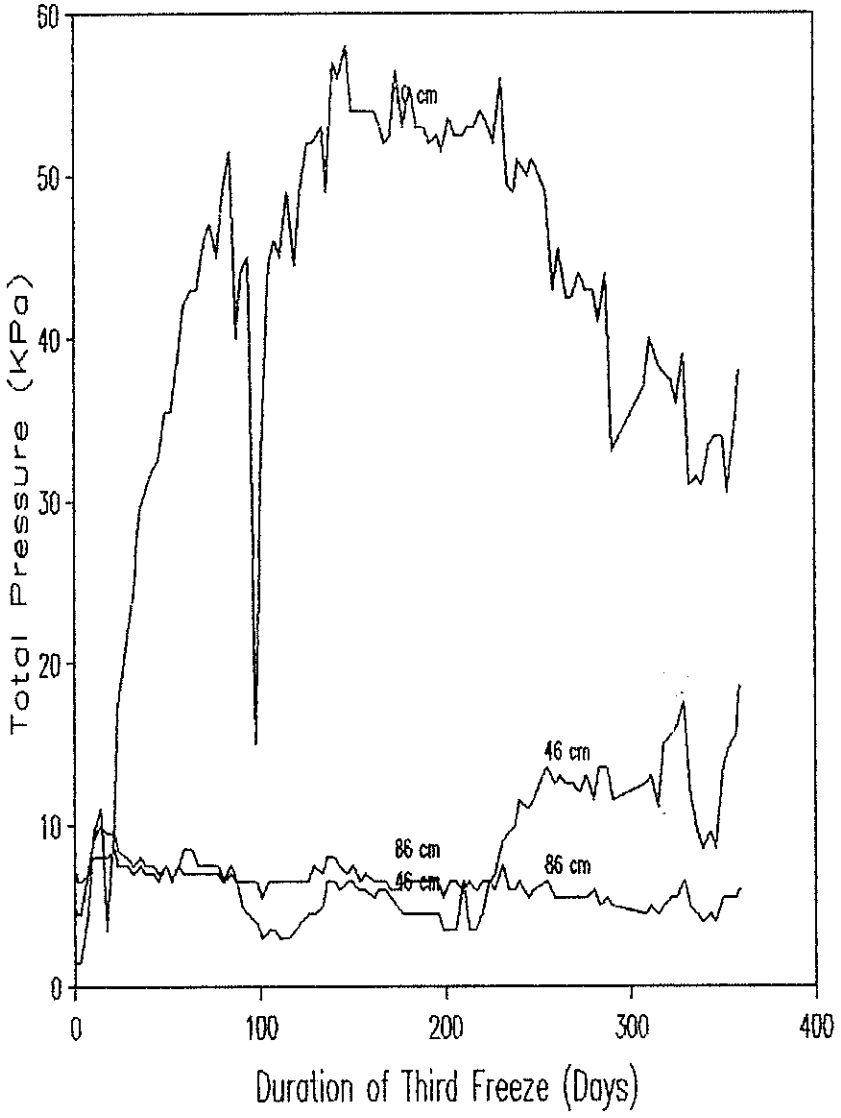
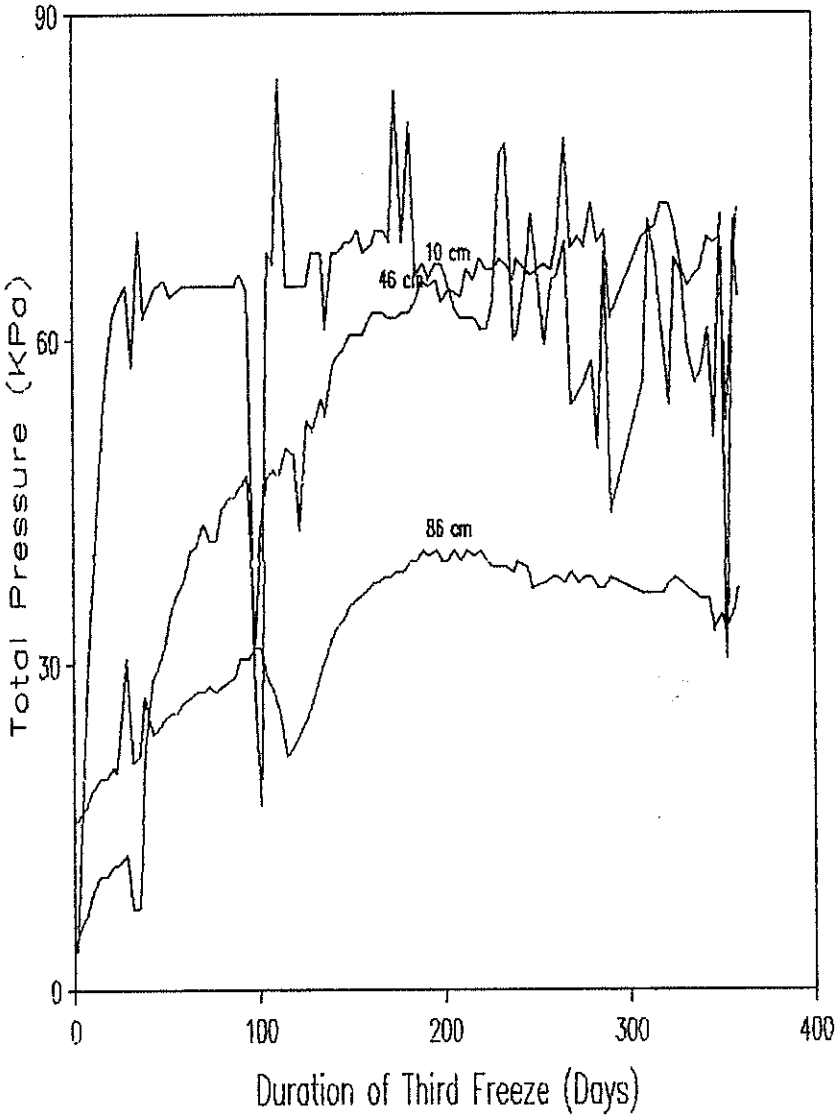


Figure 3.20 Soil Pressures from Glotzl Cells in the Sand Near the AA Cross-section



recorded at 10 cm rose more steeply than those in the silt section and attained a higher level than the one in the silt since soil freezing is quicker and more complete. The pressure at 46 cm also began to rise sharply on about day 38 when the freezing front passes this depth. The effect of the compressor shut down is also evident in the data from day 96 to day 103.

3.8 Pipe Stress

Figure 3.21 shows pipe stress for selected dates during the third freeze cycle. As observed during previous freeze cycles, the stress levels build up quite rapidly at the onset of freezing when frost heave and pipe displacement is quite rapid and large. As noted previously, two gauges broke during the second thaw period resulting in an unfortunate loss of data for the third freeze period. Fortunately, the gauges where maximum stress occurs in the pipe are still operational.

Figure 3.22 shows the pipe stress values for day 0 during the first, second and third freeze. This figure shows the residual stresses in the pipe following each thaw.

Figure 3.23 shows the values noted on day 358 for the second and third freeze. These data indicate that higher values of pipe stress were recorded during the third freeze cycle than were noted during the second.

Figure 3.21 Pipe Stress on Selected Dates During the Third Freeze

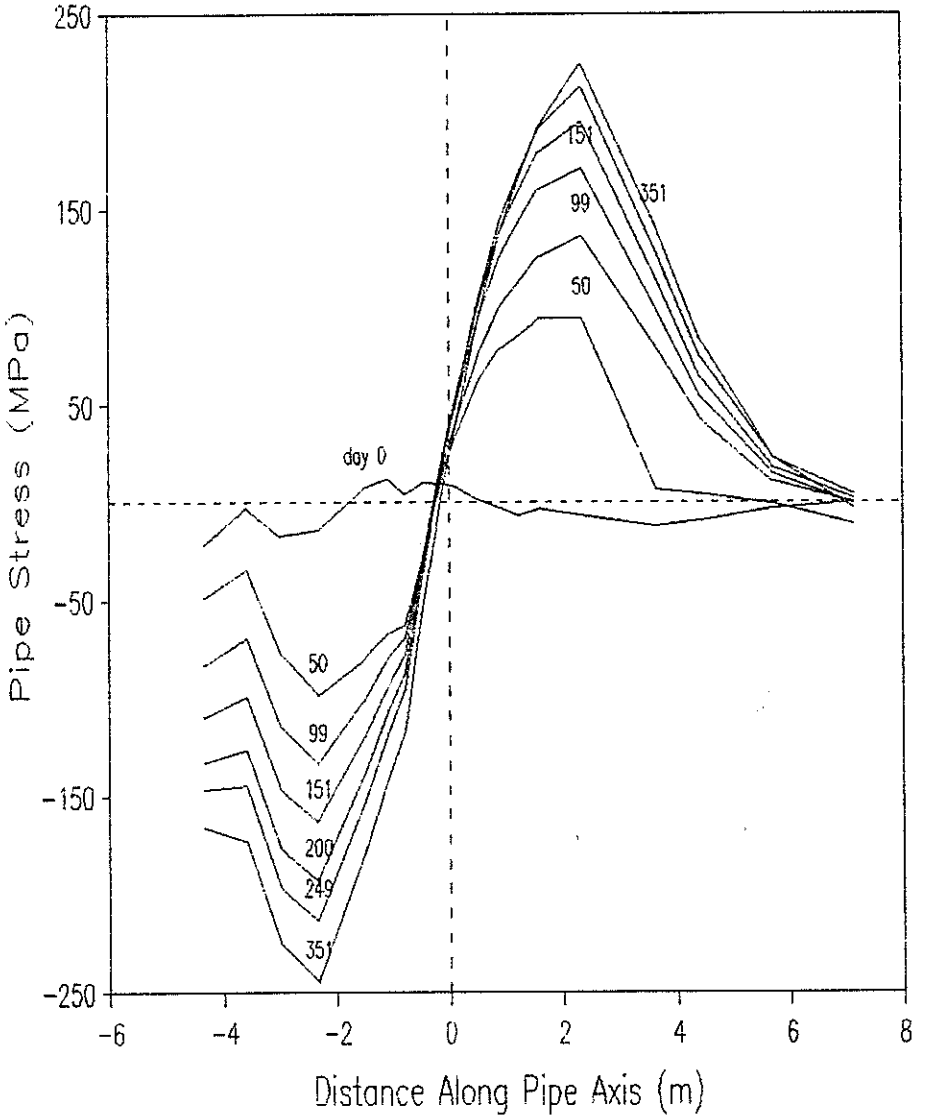


Figure 3.22 Pipe Stress Values for Day 0 for the Three Freeze Cycles

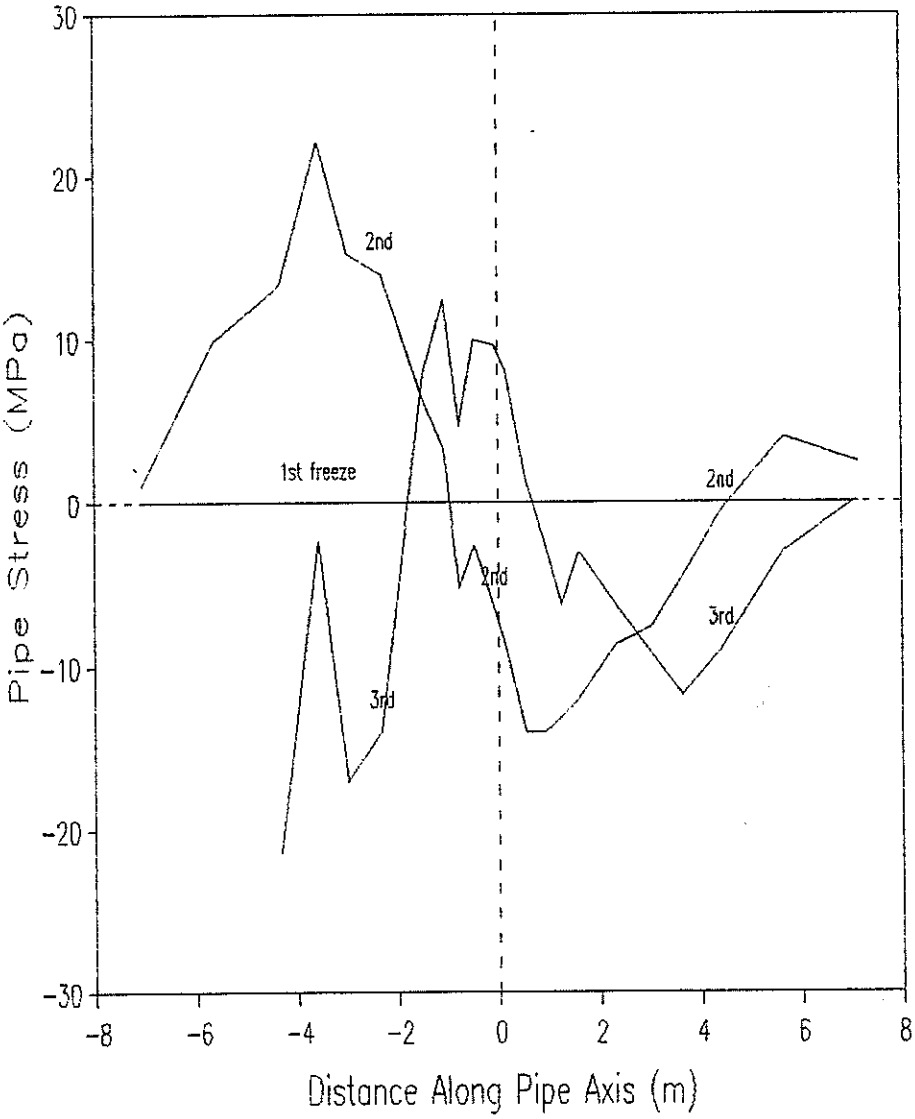
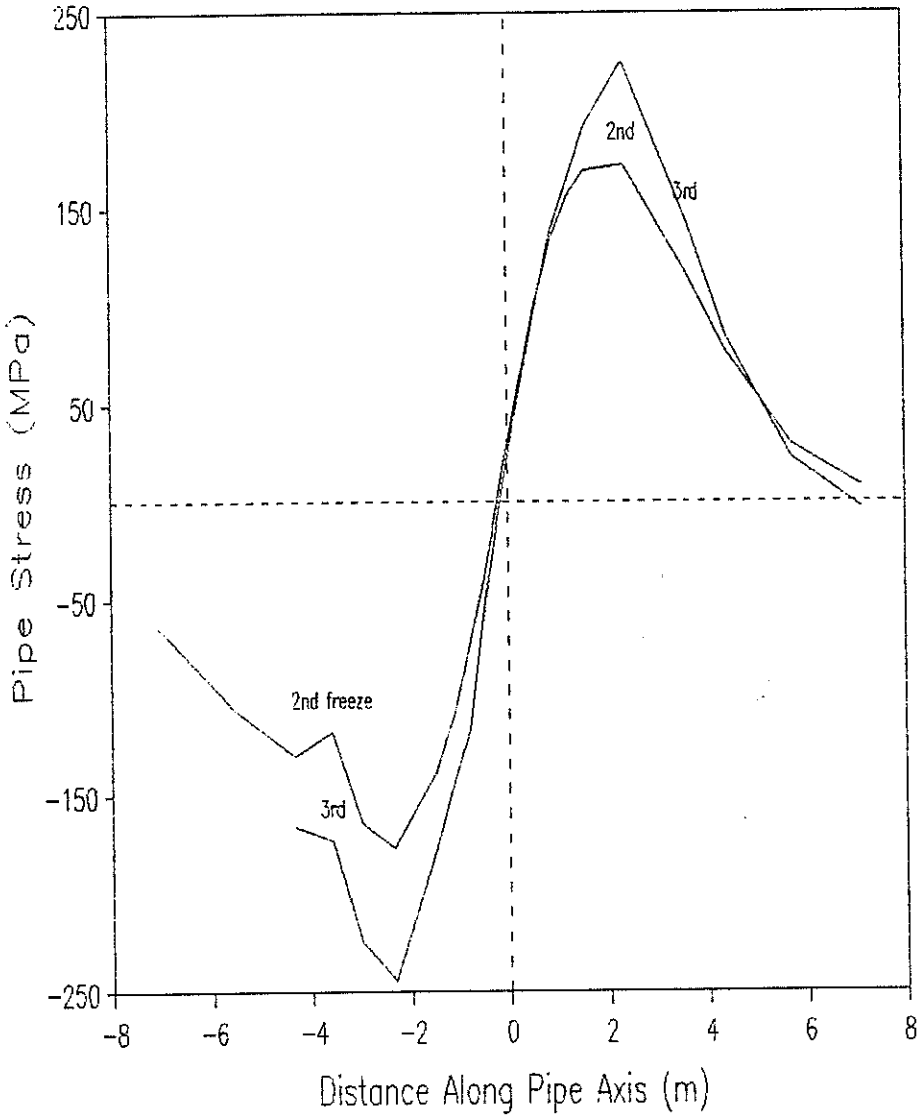


Figure 3.23 Pipe Stress on Day 358, Second and Third Freeze Cycles



IV A Detailed Examination of the Heave Characteristics at Three Sites

4.1 General

This section discusses in detail the nature and distribution of heave at sites 4, 7 and 6 in the silt section. Site 4 is 4.3 m from the sand/silt transition and 1.0 m from the pipe axis. Site 7 is 28 cm off the pipe axis and 2.0 m from the transition. Site 6 is 3.28 cm from the transition and 25.0 cm from the pipe axis.

Sites 4 and 7 were chosen since their thermal regimes were quite different yet the total heave observed was similar. Also, soil cores were obtained at these sites at the end of the freeze cycle, permitting water/ice balance calculations to be made.

Site 6 was selected since a comparison of heave results obtained by the magnet heave and telescoping heave rods could be made.

4.2 Comments About the Strain Data

Heave for each soil layer at a site was expressed as strain which is the change in a soil layer's thickness over time. The total strain in a soil layer is comprised of **initial** and **continuing strain.** Initial strain describes the displacement which occurs in close proximity to the freezing front and is the result of interstitial freezing and the freezing of water which migrates to the freezing front from unfrozen soil below. Continuing strain is the displacement which occurs in already frozen ground and is due to the freezing of interstitial water already there (as temperatures fall) or which has migrated through frozen soil. Continuing strain was observed at some distance from the freezing front, the amount being determined by the phase composition and frozen permeability of the material.

In the analysis which follows, initial strain was attributed to a soil layer when the 0 C isotherm was between magnet rings bounding a soil layer. Any strain occurring after the magnets were within frozen soil was attributed to continuing strain. This means that the amount of strain occurring in already frozen ground was **underestimated** since phase change and water migration within the frozen portion of the layer would have occurred as the freezing front advanced.

4.3 Observations for Site 4

4.3.1 Temperature and Strain Data

Soil temperatures on selected dates at site 4 are shown in Figure 4.1. Site 4's thermal regime is largely, but not completely, controlled by the ambient conditions of the facility (-0.75 C). Temperature gradients were quite small at all depths during the freeze; in fact, at the end of the freeze, the average gradient was about 0.015 C cm^{-1}.

Figure 4.2 shows the location of the 0 C isotherm at site 4 during the third freeze cycle. These data were obtained from the thermistor string located near the magnet heave array. The numbered circles on this figure denote the position of the frost front determined from displacements of the magnet rings. In general, there is a good correlation between the position of the frost line and commencement of soil heave. The data suggest that the soil begins to exhibit "frozen" characteristics at a temperature slightly less than 0 C. This is not surprising considering that the Caen silt has very little ice until temperatures are less than -0.1 C.

The strain data for this site is reproduced here as Figure 4.3. Table 4.1 summarizes the strain and temperature data for the dates when individual magnets began to heave. It is apparent from Figure 4.3 and Table 4.1 that individual soil layers

Figure 4.1 Soil Temperature at Site 4, Third Freeze

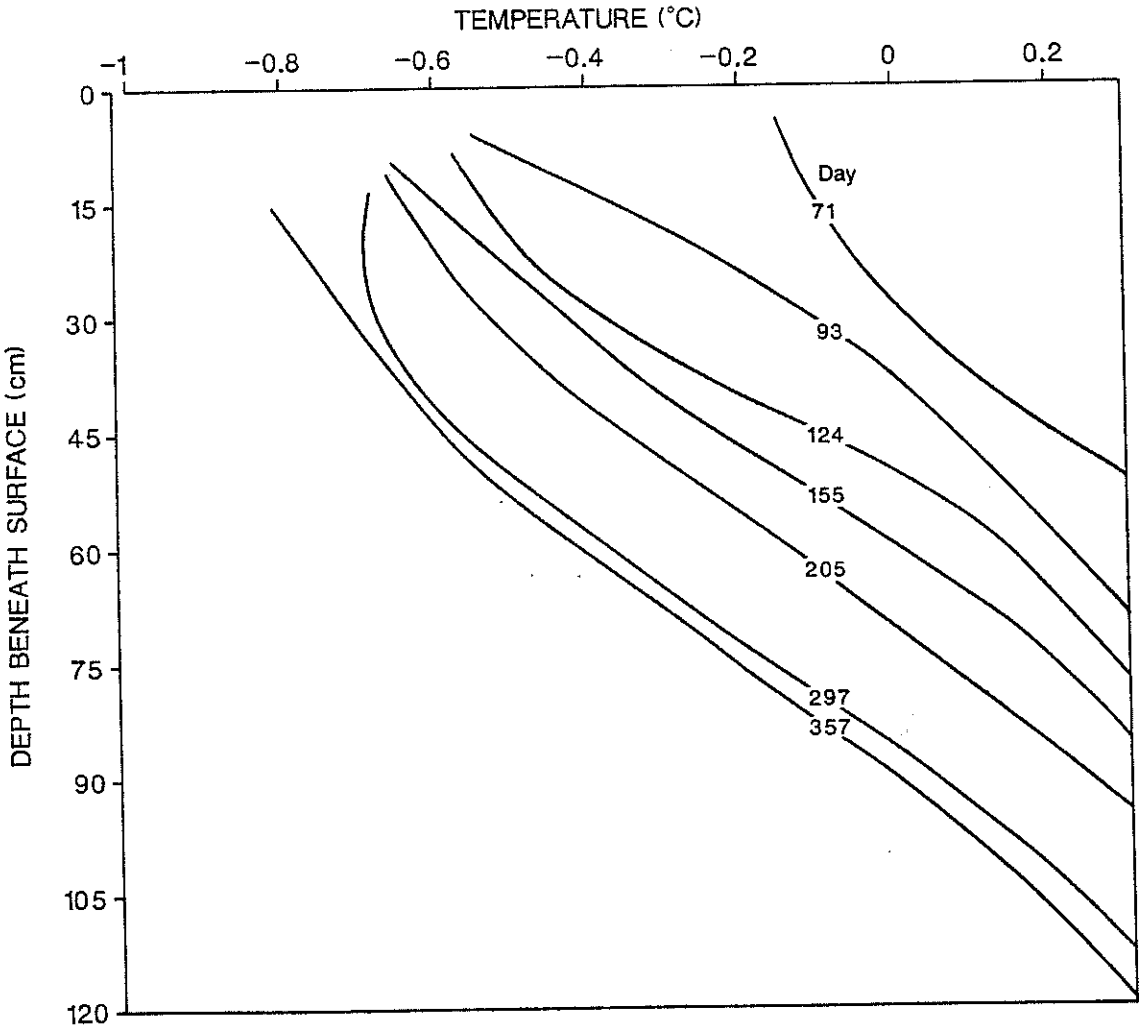


Figure 4.2 Position of the 0 C Isotherm at Site 4

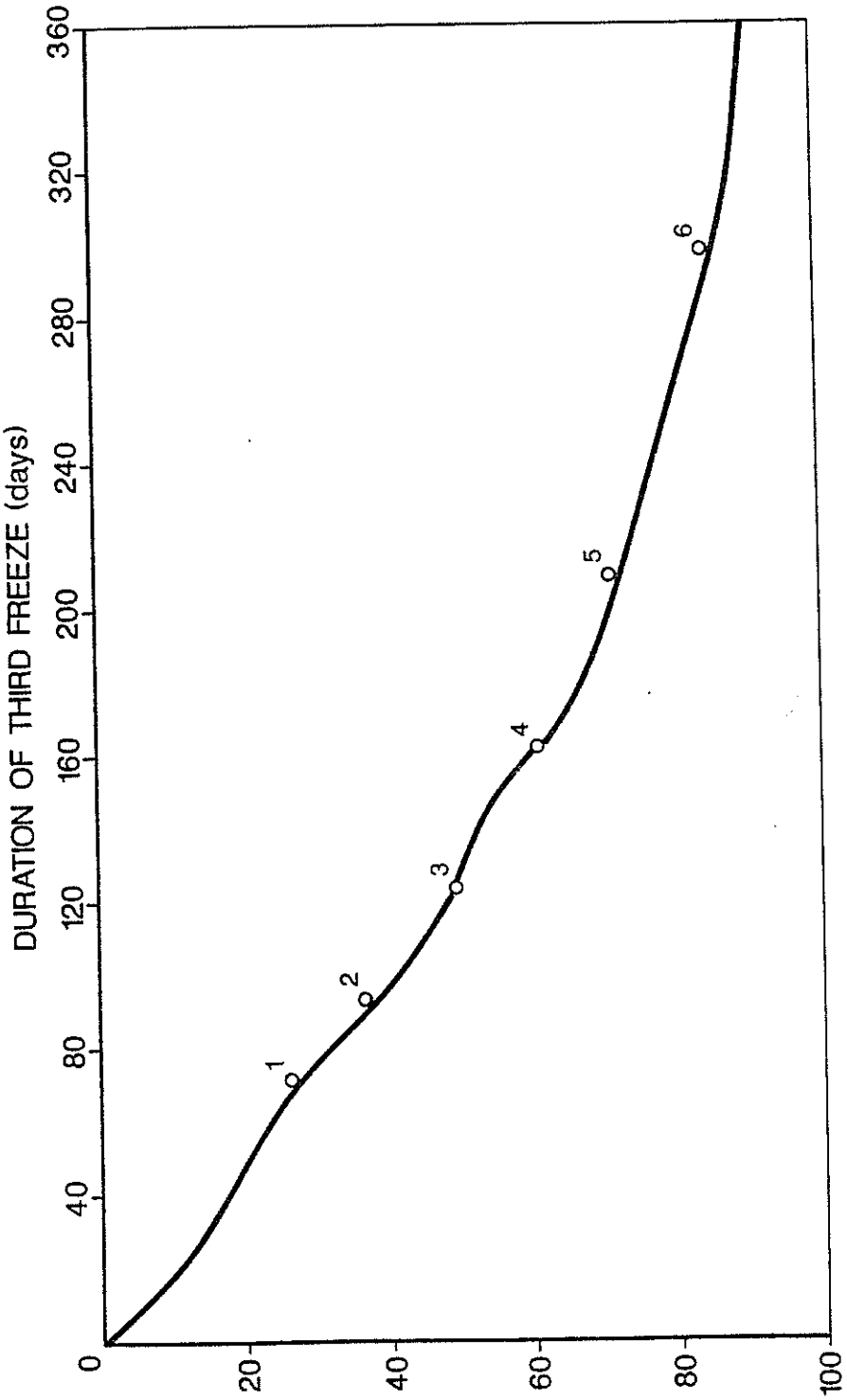


Figure 4.3 Strain at Magnet Heave Site 4

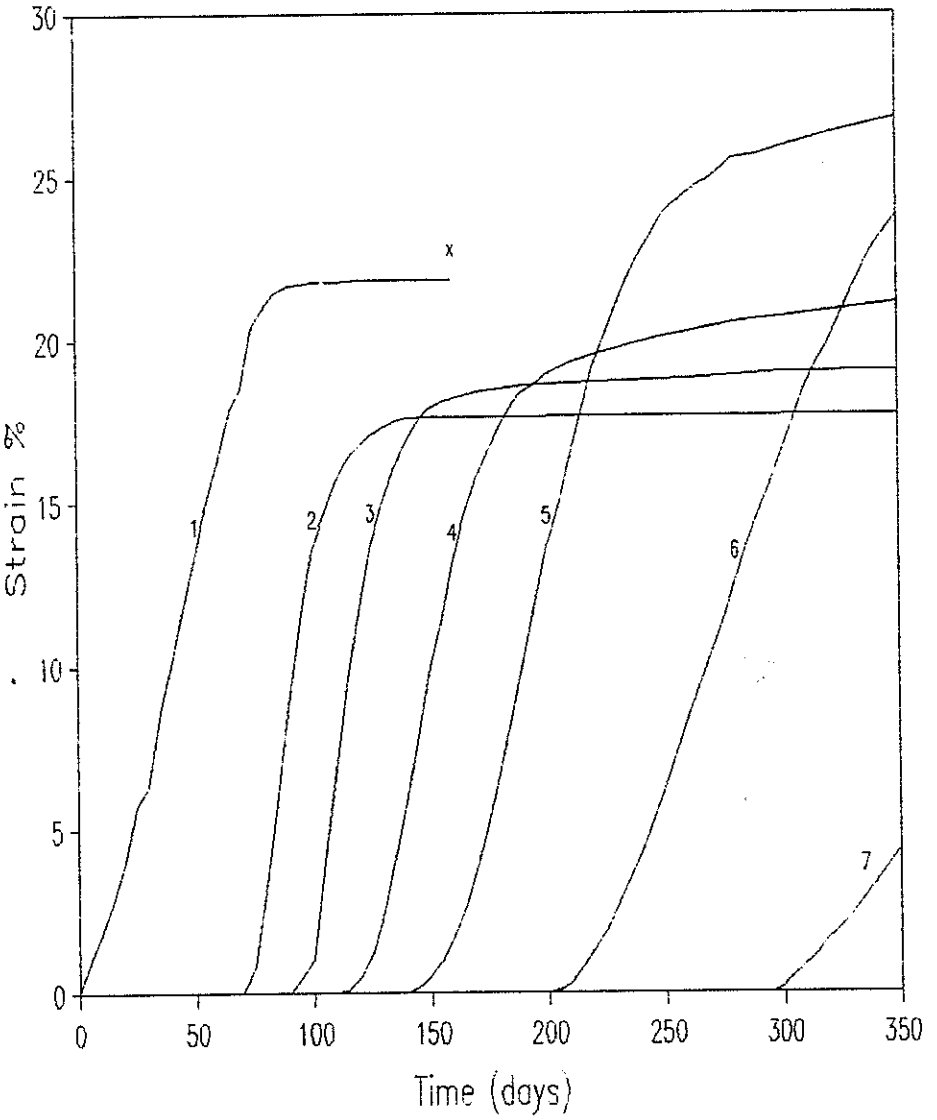


Table 4.1 **Strain and Temperature Summary for Site 4**

Magnet Number	Freeze Date[1]	Depth (cm)	Strain (%) Observed in Each Layer 1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7
1	71	25.6	0					
2	93	36.3	12.0	0				
3	124	49.3	17.6	13.2	0			
4	155	60.4	18.1	18.0	11.5	0		
5	205	70.8	18.2	18.6	19.2	15.2	0	
6	297	84.7	18.3	19.0	20.7	26.1	17.0	0
	352[2]		18.3	19.1	21.2	27.0	24.3	4.4

[1] Date on which indicated magnet begins to heave.
[2] Date on which soils cores were obtained.

Day	Approximate Temperature at Indicated Magnet 1	2	3	4	5	6	7
71	-0[3]	0.1					
93	-0.2	-0	0.9				
124	-0.4	-0.2	-0	0.1			
155	-0.5	-0.3	-0.2	-0	0.1		
205	-0.6	-0.5	-0.3	-0.1	-0	0.2	
297	-0.7	-0.6	-0.4	-0.3	-0.2	-0	0.1
352	-0.8	-0.6	-0.5	-0.4	-0.3	-0.1	0.1

[3] Indicates that the temperature is just below the ice point.
All temperatures to the nearest 0.1 C

continue to strain for some time after the layer is frozen.

To illustrate this phenomenon, consider that on day 71, magnet 1 in the profile began to heave relative to magnet 2. By day 93, the soil layer between magnets 1 and 2 had exhibited 12 % strain while the other magnets had not moved relative to one another (ie. no heave). On this date, magnet 2, just began to move relative to magnet 3 (the next soil layer). By day 124, the soil layer between magnets 2 and 3 had experienced 13.2 % strain **and** the soil layer between magnet 1 and 2 had experienced **another** 5.6 % strain (to 17.6%) **after** it was already frozen. This pattern continues, as freezing continues for all the soil layers.

The continuing strain decreases over time for all layers. However, between days 205 and 297 there are 5 soil layers over a 59 cm depth (from about 25.7 to 84.7 cm) exhibiting differing amounts of strain. At this site, soil heave was not confined to a small fringe located around the freezing front.

The temperatures at which strain persists can be found by examining Table 4.1. The approximate temperature at each magnet on the specified dates accompany the strain data. On close examination of the data, it is apparent that strain in already frozen ground really slows down when both magnets are at temperatures colder than -0.3 C. For example, after day 155, the strain exhibited in the soil layer between magnets 1 and 2 is negligable. This corresponds to the phase composition and frozen hydaulic conductivity data whereby the soil is fairly ice rich and impermeable.

4.3.2 The Water/Ice Balance at Site 4

This section discusses the accumulations of ice within the profile as evidenced by the strain data and information obtained during the soil coring program undertaken at the end of the experiment.

Values for the gravimetric water content obtained at site 4 for the start and end of the third freeze cycle are shown in Figure 4.4. The values for day 0 generally show that the soil was slightly under-saturated in the top 40 cm of the profile and essentially saturated below this point. Even though the water table is maintained at 90 cm beneath the soil surface, the capillary rise of the silt will ensure almost complete saturation above this point.

On day 352, the 0 C isotherm was 91 cm beneath the soil surface and about 15 cm of heave had been observed. The water contents in the top 91 cm of the soil profile were substantially greater than they had been at the start of the freeze cycle. The high value of water content in the 14 to 23 cm layer seems to be anomalous since there was no evidence of exceptional iceiness in photos taken during core recovery.

Figure 4.5 shows the water/ice balance for this site. The figure shows the distribution of ice and unfrozen water in the profile on a volumetric basis. The values were calculated from the total gravimetric water content and dry density information obtained during the coring program. Since the soil would contain unfrozen water, the total gravimetric water content was partitioned into ice and water using unfrozen water content versus temperature information.

In the figure, "water" stands for the volumetric unfrozen water content; "ice", the volumetric ice content and, "total", the total volumetric ice-water content which is the sum of both phases. In general, the profile showed about a 10% increase in volumetric water content from the initial average of 35 cm^3 cm^{-3}, %.

Values of total water content were also calculated from the strain data assuming that the observed strain could be attributed to ice accumulation and that the soil profile had an average water content of 35 cm^3 cm^{-3}, % and dry density of 1.7 g cm^{-3} at the start of the freeze cycle. The water content profile for comparable soil

Figure 4.4 **Gravimetric Water Contents at Site 4 at the Start and End of the Third Freeze**

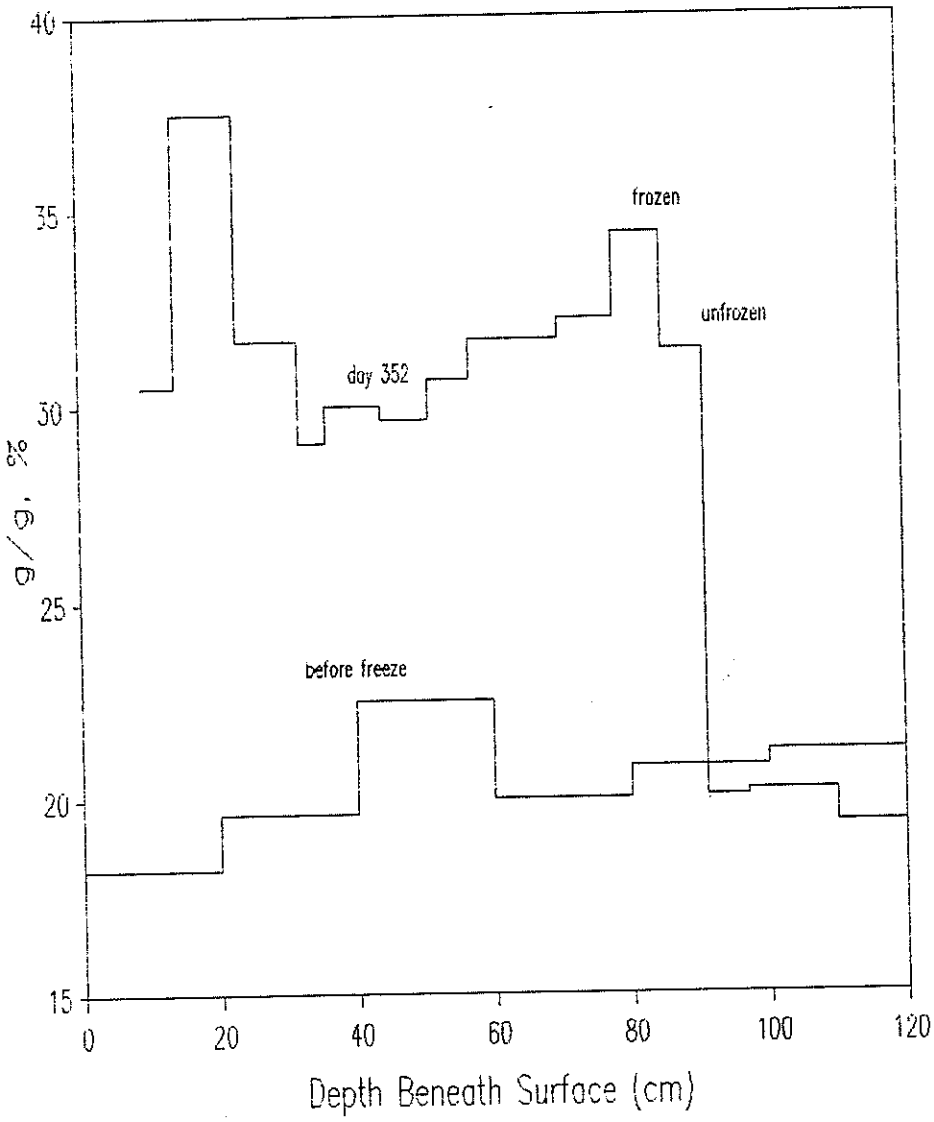
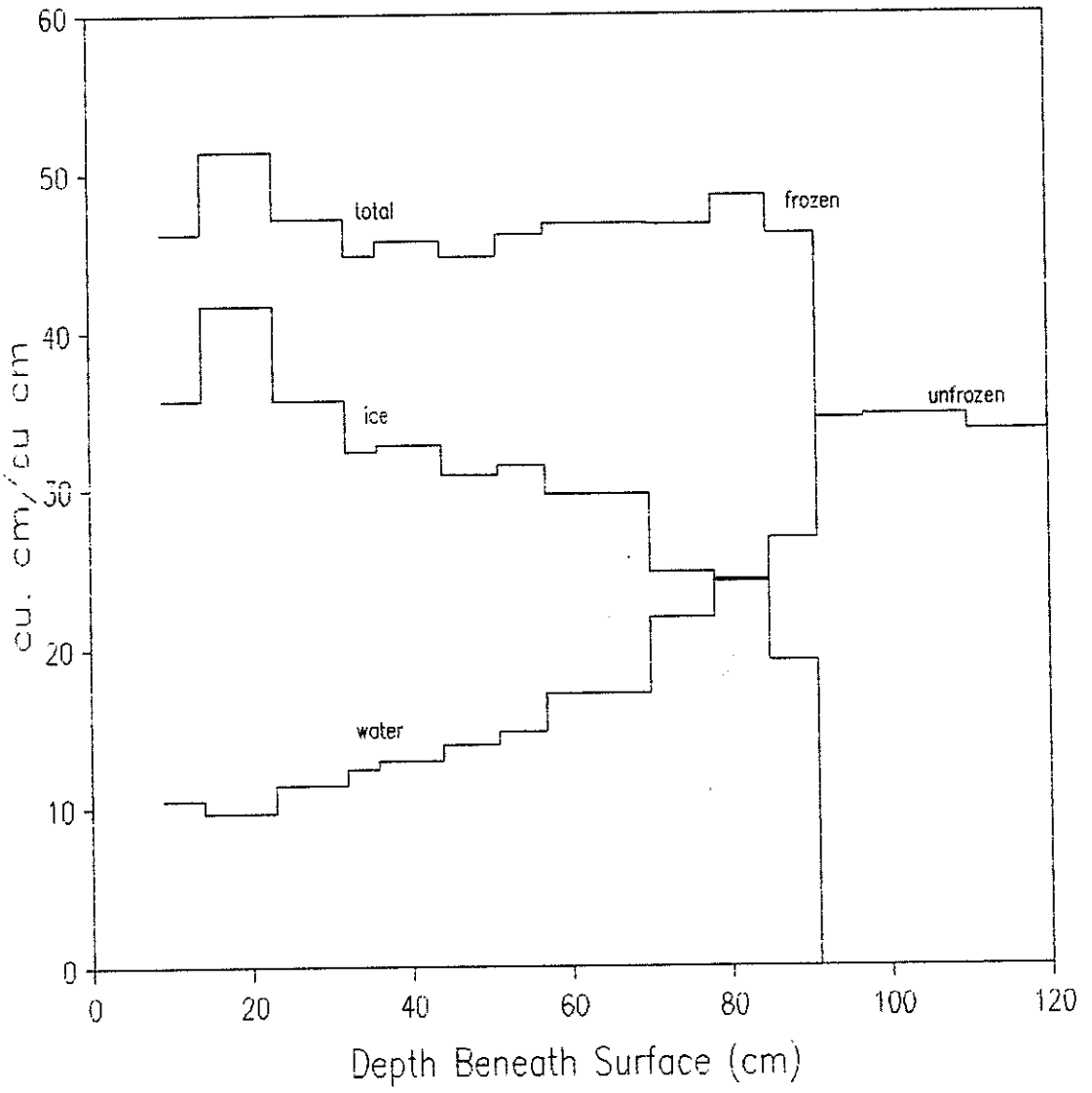


Figure 4.5 Water-Ice Balance at Site 4



layers was calculated from the coring information. The results are tabulated in Table 4.2 and show good agreement.

Table 4.2

Total Water Content Values at Site 4: from Soil Coring and Strain Data

Depth Beneath Surface (cm)	Total Volumetric Water Content (cm^3 cm^{-3}, %)	
	Coring Data	Strain Data
0.0 - 25.1	47.7	45.4
25.1 - 36.2	46.2	45.4
36.2 - 48.9	45.7	45.8
48.9 - 60.6	46.1	46.7
60.6 - 72.0	46.8	49.1
72.0 - 85.1	47.7	48.0
85.1 - 95.1	41.3	38.1

4.4 Observations for Site 7

4.4.1 Temperature and Strain Data

Soil temperatures on selected dates at site 7 are shown in Figure 4.6. This site is located at 28 cm from the pipe axis, hence, its thermal regime is strongly influenced by pipe temperatures. The temperatures were generally much colder than at site 4 and temperature gradients were much larger. The position of the 0 C isotherm is shown in Figure 4.7. The numbered circles denote the position of the frost front determined from displacements of the magnet rings as was done for site 4.

Strain data for site 7 is shown in Figure 4.8. Essentially no strain was exhibited in the soil layer extending from the soil surface to about 49.5 cm (magnets 1 to 4). This layer froze quite quickly and remained quite cold (-1.5 to -2.8) for the duration of the freeze. The strain and temperature data for this site are summarized in Table 4.3 for the dates when individual magnets began to heave. Soil layer 1 is between magnets 4 and 6. Magnet 5 could not be detected during the experiment and was possibly broken during installation.

The data in Table 4.3 shows that the temperatures were generally much colder than was found at site 4 and strain in already frozen ground persisted for a shorter period of time. For example, the layer bounded by magnets 4 and 6 exhibited no strain after day 47 when both magnets were colder than -0.4. Similarly, sometime between day 70 and 113, the strain in the layer bounded by magnets 6 and 7 essentially stopped. The pattern continues throughout the profile.

4.4.2 Water/Ice Balance at Site 7

Figure 4.9 shows the gravimetric water content data for site 7 before and after the freeze cycle. The high values of water content in the 40 to 60 cm layer could be anomolous since there was little evidence in photos of the recovered cores that excess iciness would be expected.

The water/ice balance for this site is shown in Figure 4.10 and the values were determined in the manner discussed in section 4.3.2. Again, the values for the 40 to 60 cm layer could be high.

Values of total water content were calculated from the strain data as discussed previously. The results are shown in Table 4.4. In general, the agreement is fairly good although some discrepancy occurs in the 0 to 49.6 and 49.6 to 75.6 cm layers. These discrepancies could be the result of the high water contents in the 40 to 60 cm layer determined from coring data or in the calculation from strain data (ie. assumption of a uniform density and water content may not be applicable).

Figure 4.6 **Soil Temperatures at Site 7**

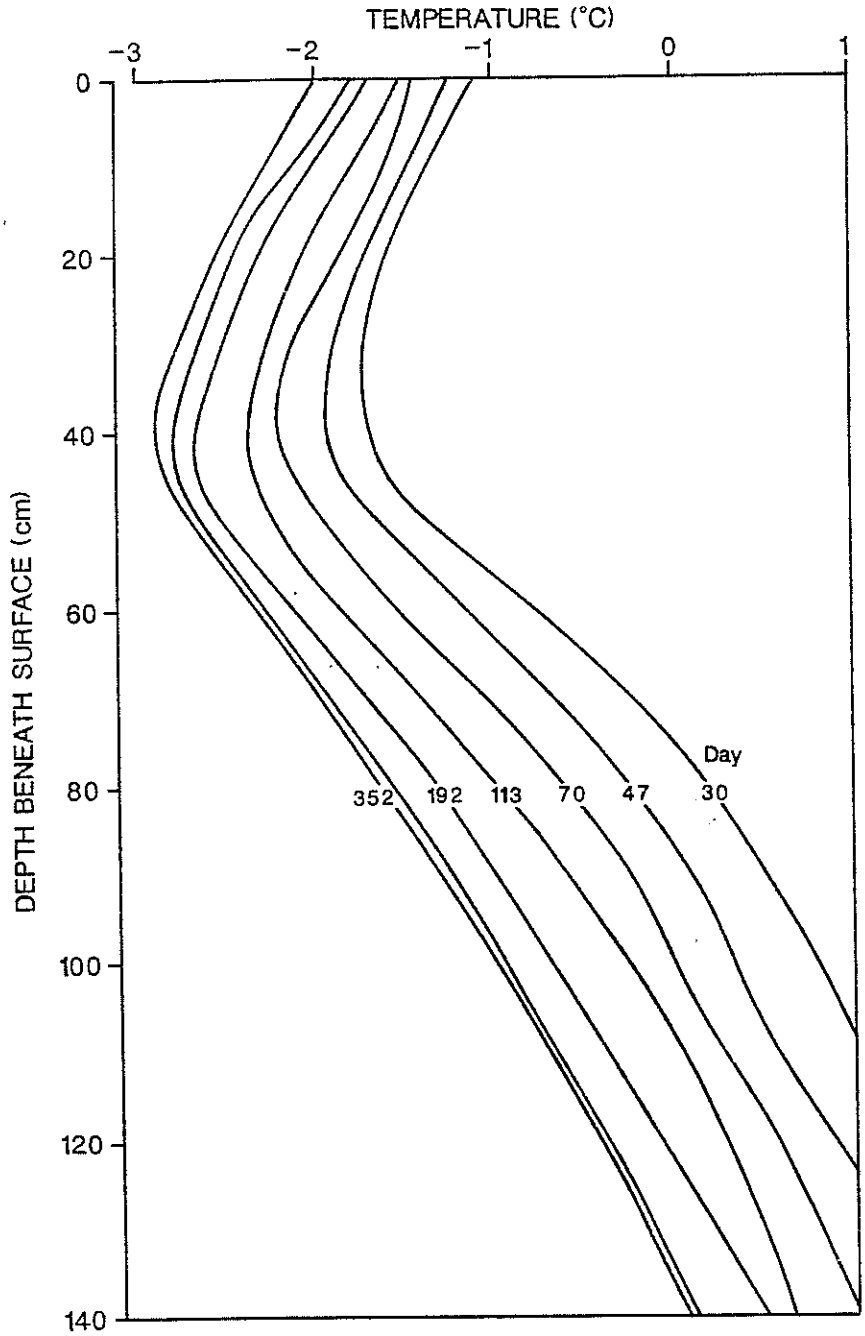


Figure 4.7 Position of the 0 C Isotherm at Site 7

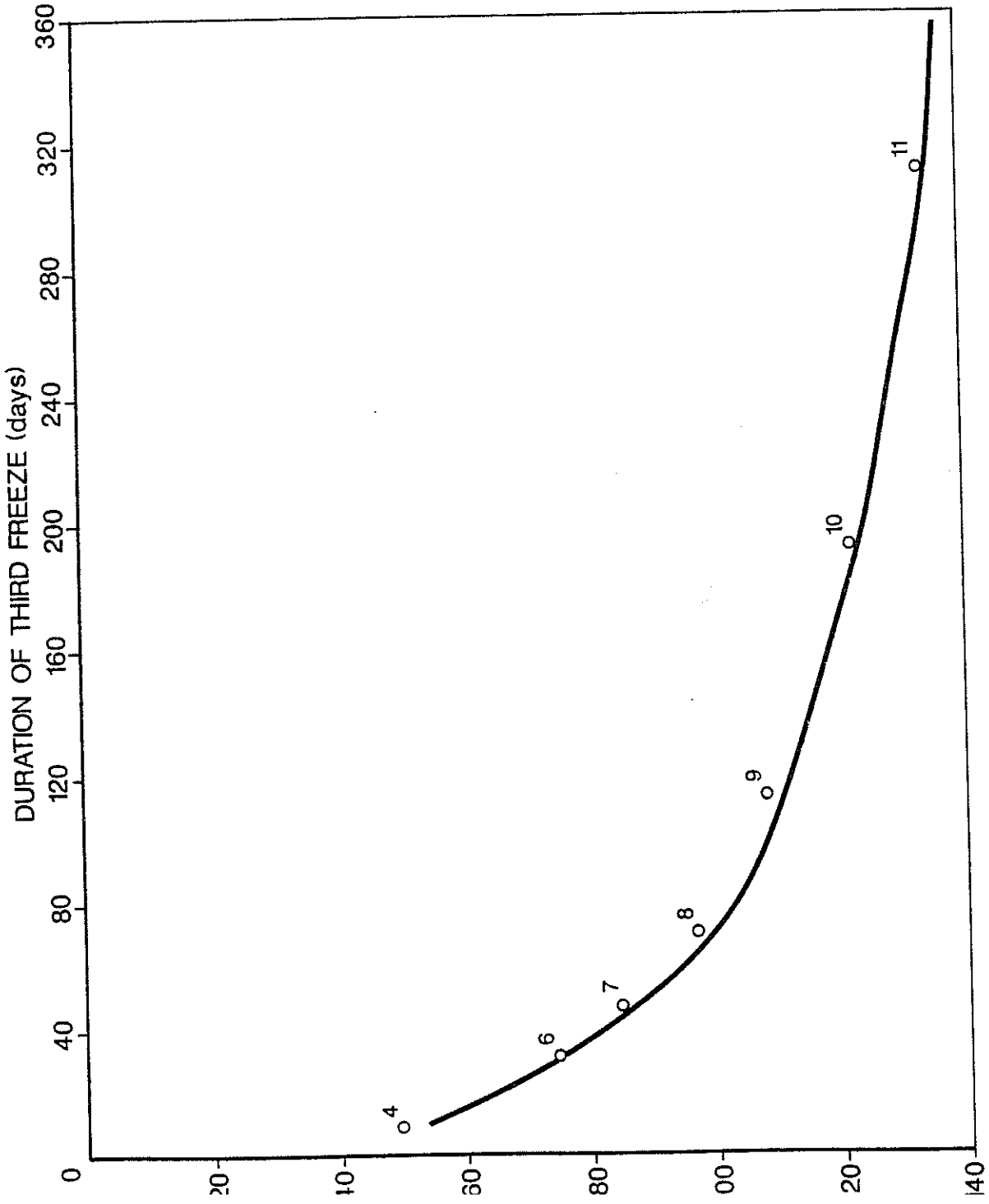


Figure 4.8 Strain Data for Site 7

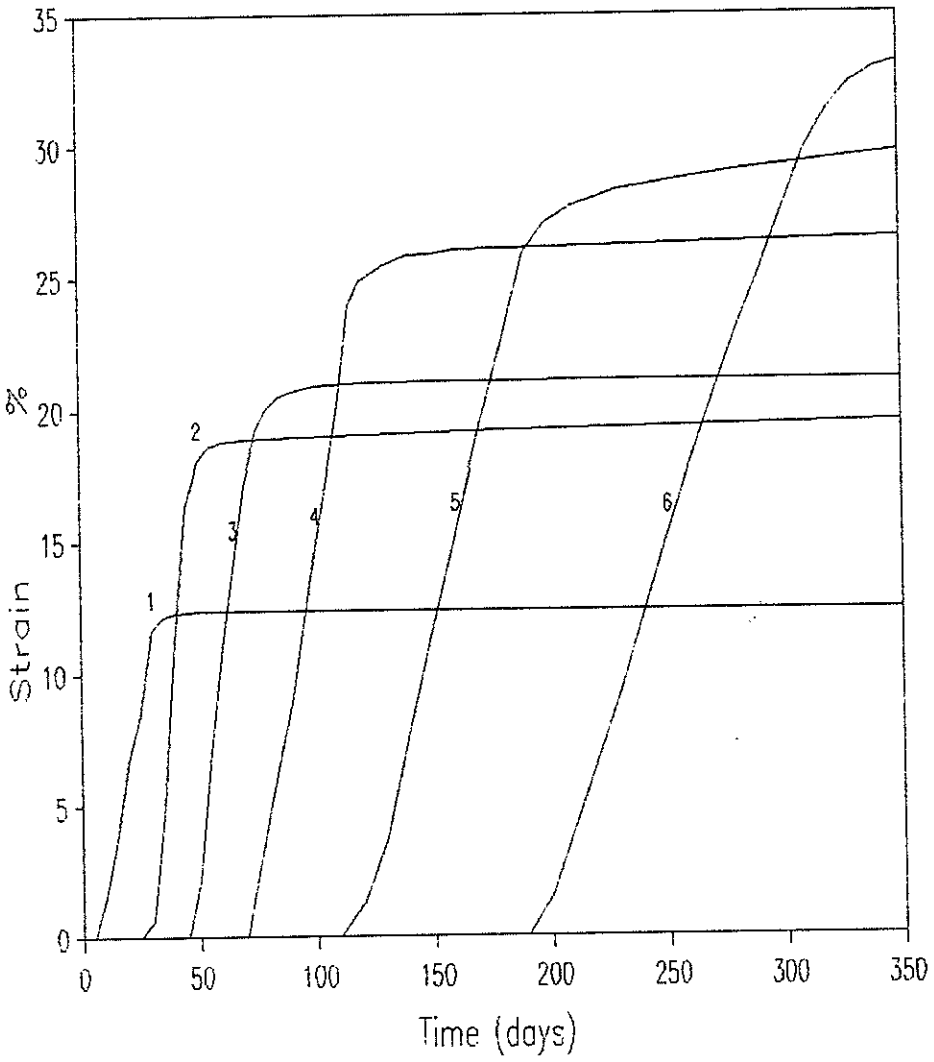


Table 4.3 Strain and Temperature Summary for Site 7

Magnet Number	Freeze Date[1]	Depth (cm)	Strain (%) Observed in Each Layer 4 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11
4	8	49.5	0					
6	28	75.3	11.0	0				
7	47	84.4	12.4	17.3	0			
8	70	96.5	12.4	18.0	17.0	0		
9	113	108.0	12.4	19.0	21.0	22.3	0	
10	192	121.9	12.4	19.2	21.0	26.2	26.2	0
11	310	134.5	12.4	19.4	21.1	26.4	29.3	29.7
	352[2]		12.4	19.4	21.1	26.5	29.7	33.2

[1] Date on which indicated magnet begins to heave.
[2] Date on which soils cores were obtained.

Day	Approximate Temperature at Indicated Magnet 4	6	7	8	9	10	11
30	-1.4	-0[3]					
47	-1.6	-0.4	-0				
70	-1.9	-0.8	-0.4	-0			
113	-2.2	-1.2	-0.8	-0.3	-0		
192	-2.5	-1.5	-1.2	-0.7	-0.4	-0	
310	-2.6	-1.7	-1.4	-1.0	-0.6	-0.2	-0
352	-2.7	-1.8	-1.5	-1.1	-0.8	-0.3	-0.1

[3] Indicates that the temperature is just below the ice point.
All temperatures to the nearest 0.1 C

Figure 4.9 Gravimetric Water Contents at Site 7 at the Start and End of the Third Freeze

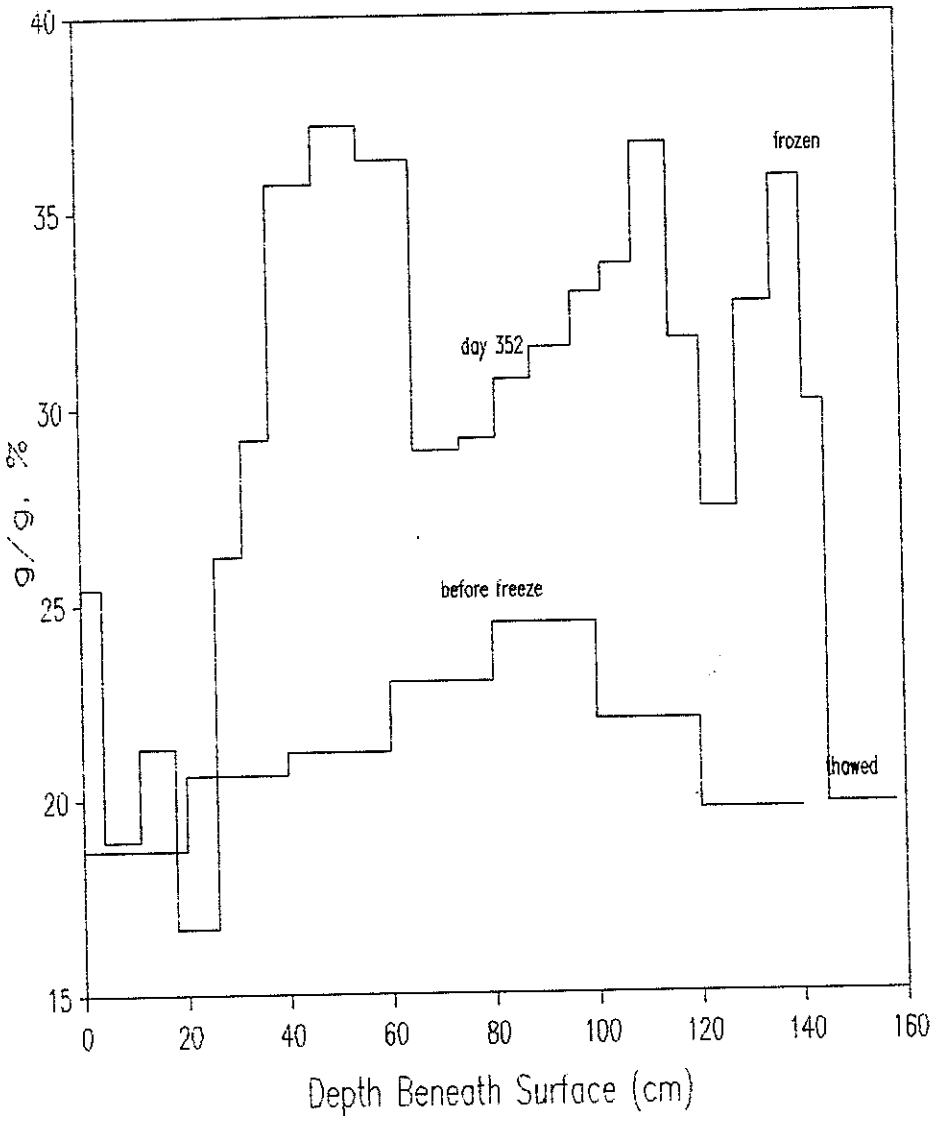


Figure 4.10 Water/Ice Balance at Site 7 and the End of the Third Freeze

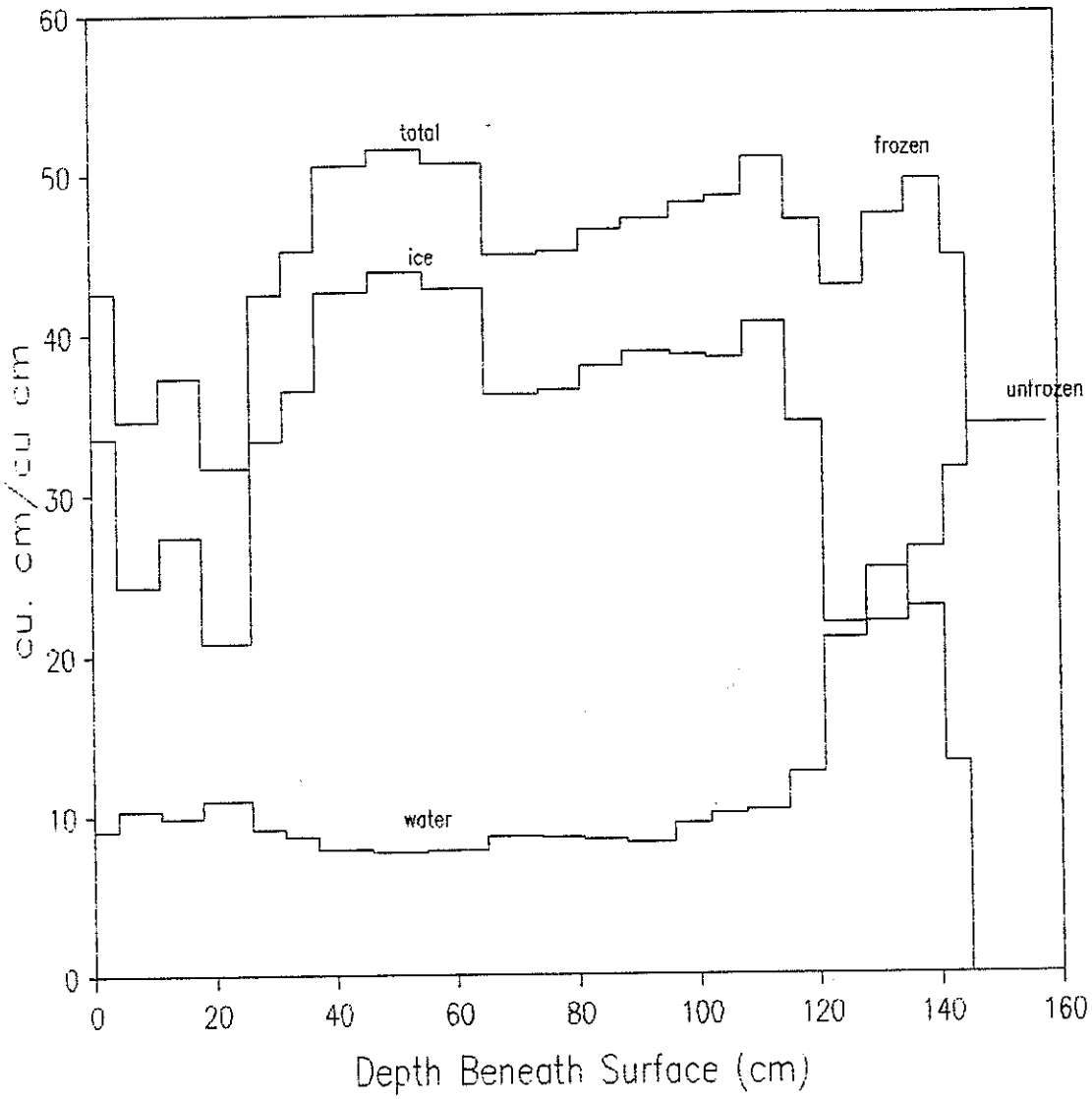


Table 4.4

Total Water Content Values at Site 7: from Soil Coring and Strain Data

Depth Beneath Surface (cm)	Total Volumetric Water Content ($cm^3\ cm^{-3}$, %)	
	Coring Data	Strain Data
0.0 - 49.6	41.3	35.2
49.6 - 75.3	48.5	42.6
75.3 - 84.3	45.6	43.7
84.3 - 96.8	47.0	47.5
96.8 - 108.2	48.3	48.7
108.2 - 122.2	48.5	49.9
122.2 - 135.1	45.3	51.6

4.5 Observations for Site 6

The proximity of a set of telescoping heave rods to magnet heave site 6 offered the chance to compare the observed patterns of total heave and differential strain. Magnet heave site 6 is located in the silt 3.18 m from the sand-silt transition and 25.0 cm off the pipe axis and the telescoping heave rods are located 3.45 from the transition and 26.0 cm off the pipe axis.

The position of the 0 C isotherm is shown in Figure 4.11. The open circles denote the position and dates that individual magnet rings began to move. These correspond well with the position of the frost front but do suggest that the temperature was slightly colder than the ice point before the soil exhibited frozen characteristics.

The total heave measured by both devices is shown in Figure 4.12 and the results are very comparable. The strain patterns in individual soil layers are shown in Figures 4.13 and 4.14. The position of the magnets and telescoping heave rods within the soil profile at the start and end of the freeze cycles are given in Table 4.5. As is shown, the different soil layers overlap.

The strain pattern as shown by the magnet heave data in Figure 4.13 is the same as that observed at other sites. Generally the amount of strain increased the deeper the soil layer was within the profile. This reflects lower frost penetration rates which permitted greater ice accumulations at the freezing front and within the frozen soil. The seemingly high total strain in layer 1 is undoubtedly due to the higher initial water content in the 60 to 80 layer (0.322 $g\ g^{-1}$) compared with the average of the profile (0.22 $g\ g^{-1}$). As temperatures fell below the ice point, this excess water would freeze producing a strain greater than expected.

The strain pattern obtained with the telescoping heave rods at this site is shown in Figure 4.14 and is very similar to that of the magnet data. Both devices show that strain continues in already frozen ground as was observed at other sites.

Figure 4.11 Position of 0 C Isotherm at Site 6

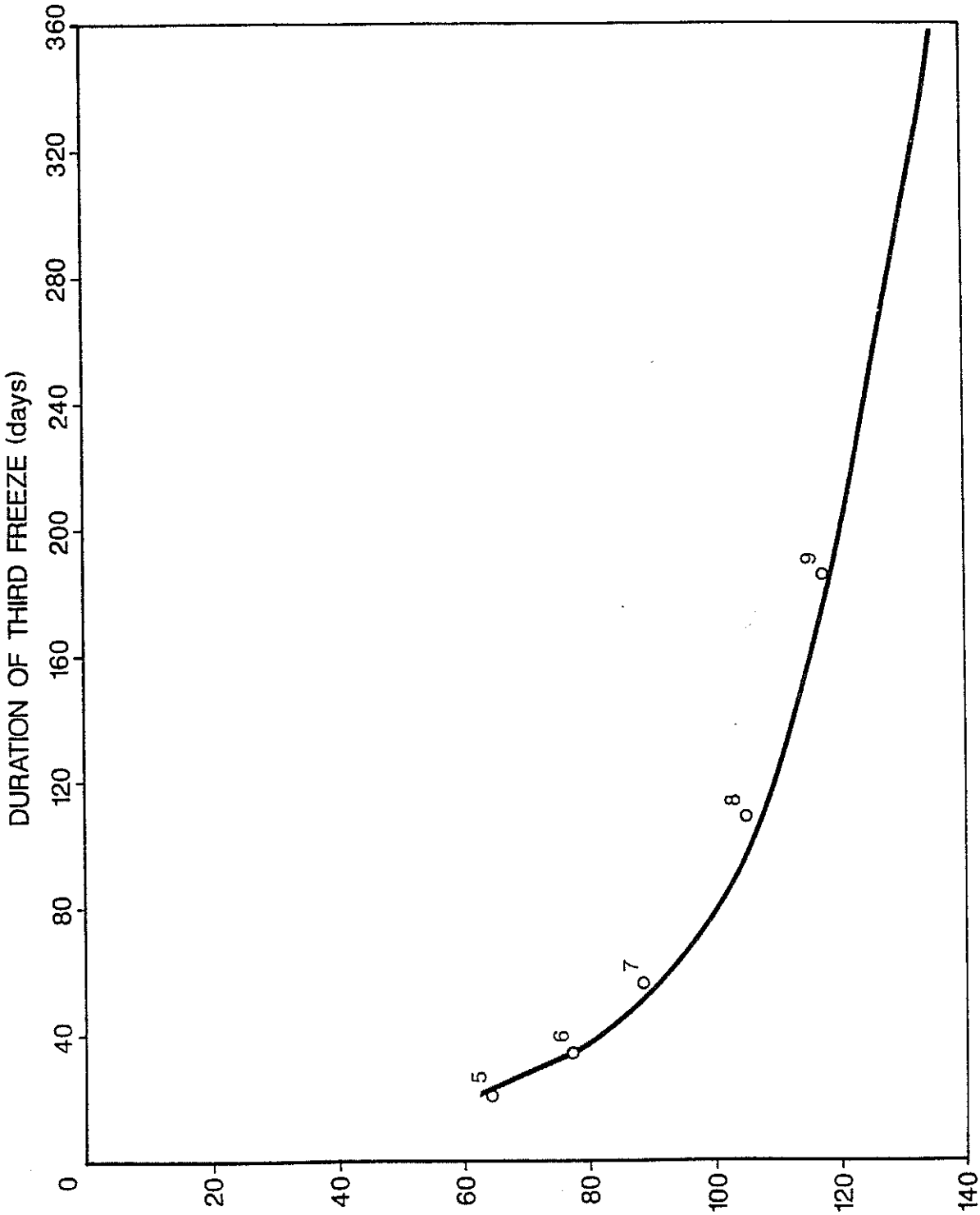


Figure 4.12 **Total Heave at Site 6 Determined from Magnet Heave Device and Telescoping Heave Ro**

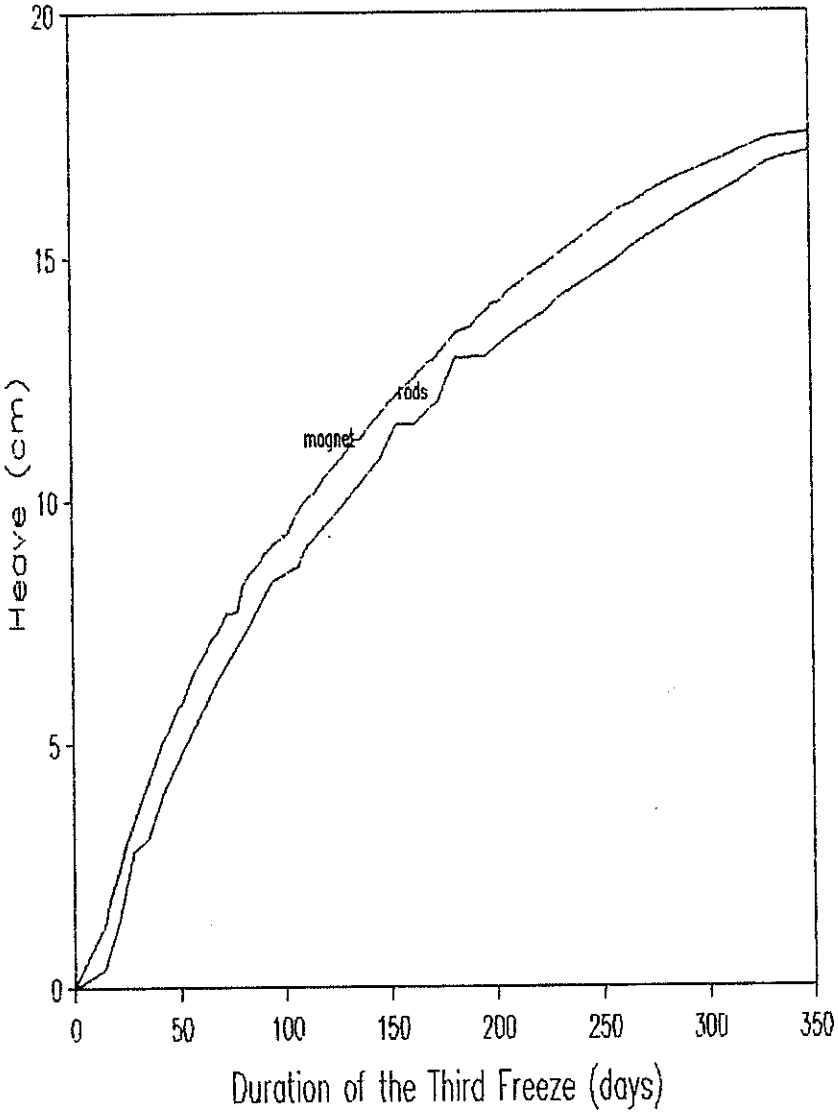


Figure 4.13 Strain at Magnet Heave Site 6

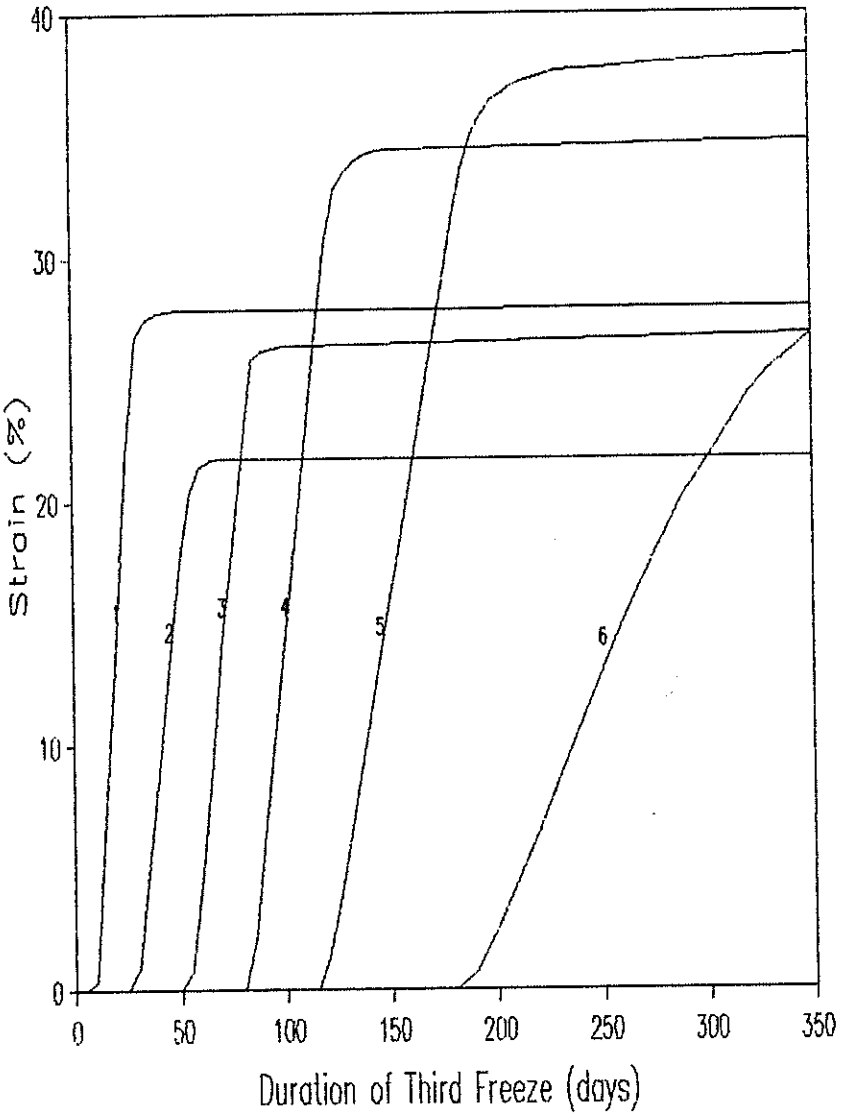


Figure 4.14 Strain at Magnet Heave Site 6 Measured with Telescoping Heave Rods

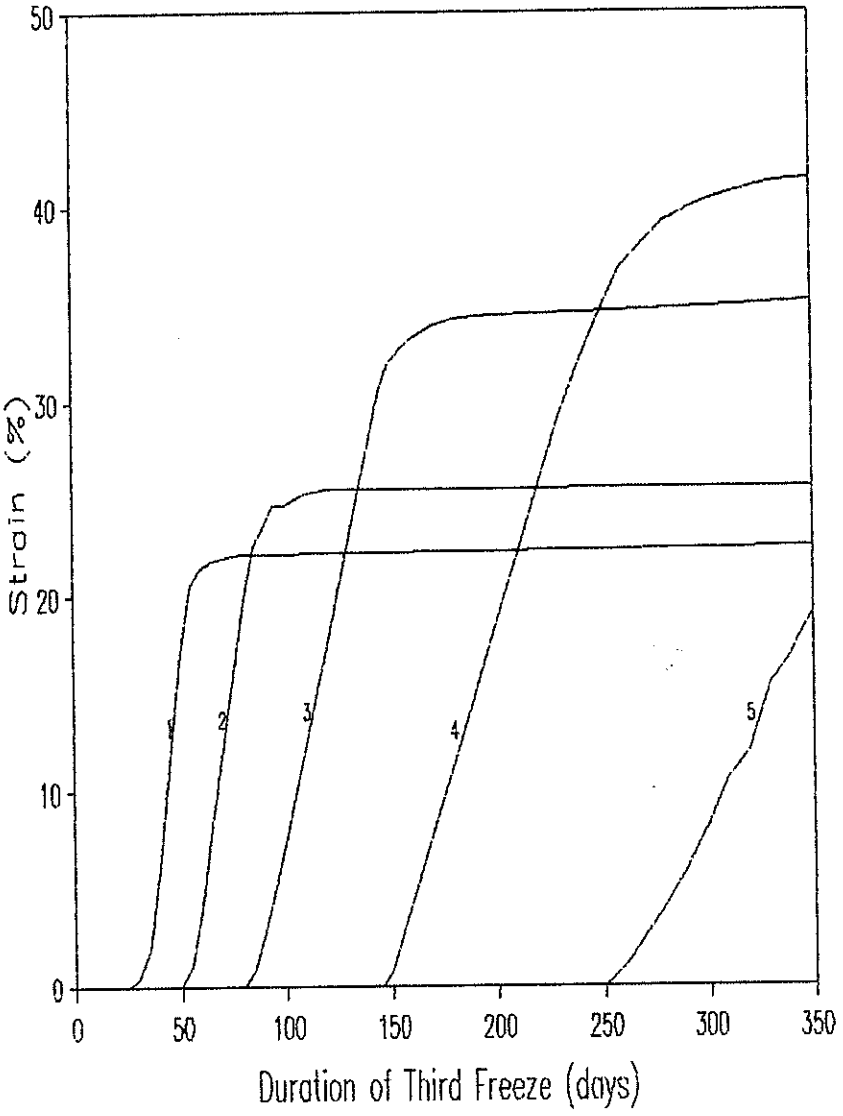


Table 4.5 **Position of Magnet Rings and Telescoping Heave Rods at Magnet Heave Site 6 at the Start and End of the Third Freeze Cycle**

		Depth Beneath Surface (cm)			
Magnet Heave Device	**Layer**	**Day 0**		**Day 357**	
	1	62.0	71.0	62.7	74.2
	2	71.0	84.2	74.2	90.3
	3	84.2	92.7	90.3	101.0
	4	92.7	98.8	101.0	109.3
	5	98.8	107.5	109.3	121.3
	6	107.5	121.4	121.3	138.9
Telescoping Heave Rods	1	74.5	84.7	77.5	90.0
	2	84.7	94.7	90.0	102.6
	3	94.7	104.8	102.6	116.1
	4	104.8	125.2	116.1	130.2
	5	125.2	135.7	130.2	142.4

V Third Thaw Cycle

5.1 General

The third thaw cycle began on February 25, 1987 and was completed on May 21, 1987. During this period, the pipe temperature control was shut off and the temperature in the facility was maintained at 4 C.

During the time preceeding the fourth freeze cycle, intermittent observations were continued and a program of instrument repair and re-instrumentation was undertaken. Specifically, the Petur devices for measuring soil pressures were excavated, repaired and re-installed so that the relationship between soil pressure and frost heave could be studied in more detail. Details of the re-instrumentation will be reported in a later report.

5.2 Observations During the Third Thaw

Figure 5.1 shows the pattern of soil temperature at site # 2 on selected dates. This site is 25 cm from the pipe axis near the BB cross-section in the silt. By about day 11 of the thaw, temperatures were generally warmer than -0.5 C and the soil had thawed to a depth of about 21 cm. Between day 11 and 29, thawing progressed downward from the soil surface and upward from the maximum depth of frost penetration such that the soil layer between 43 and 120 cm remained frozen. By day 50, only a small layer between 80 and 107 cm remained frozen. After about day 70, the ground was completely thawed and continued to warm to almost isothermal conditions by day 84.

Figure 5.2 shows the pipe shape during the third thaw. The most notable feature is elevation of the pipe after the completion of thaw (about day 70). The pipe has continued to be jacked up within the soil profile by successive freeze-thaw cycles. The maximum deflection is about 7.7 cm compared with 3.7 cm at the conclusion of the second thaw.

A cavity was observed beneath the pipe when excavations were made for the re-installation of the Petur devices. This cavity formation was observed at the conclusion of the second thaw as well. Photographs of the cavity and more detailed observations are being completed and will be reported later.

The change in soil pressures as observed by the Glotzl cells is shown in Figures 5.3 and 5.4 for the sand and silt section respectively.

The pressure levels at 10 and 46 cm beneath the pipe in the sand section (Figure 5.3) dropped quite rapidly during the first 15 days of thaw but remained relatively constant until about day 42 when the pressure levels dropped quite markedly, undoubtedly corresponding to the complete thaw of the soil.

The pressure levels beneath the pipe in the silt section are shown in Figure 5.4. The values at 10 cm show a fairly rapid decline over the first 15 days of thaw as the thaw front advanced downward within the soil profile. Between day 15 and 65, the change was much more gradual until complete thaw occurred.

The pressure levels at 46 cm beneath the pipe dropped gradually until about day 30 as thawing progressed. Between about day 30 and 60, a marked increase in pressure was observed while the cell was still within the frozen annulus. The reasons for this are not readily apparent but suggest a concentration of stresses within the frozen annulus. A similar pattern, but to a lesser degree, was observed for the 86 cm cell.

5.3 Summary

Work is currently being undertaken to compare observations between the various

Figure 5.1 **Ground Temperatures at Site 2 in the Silt during the Third Thaw**

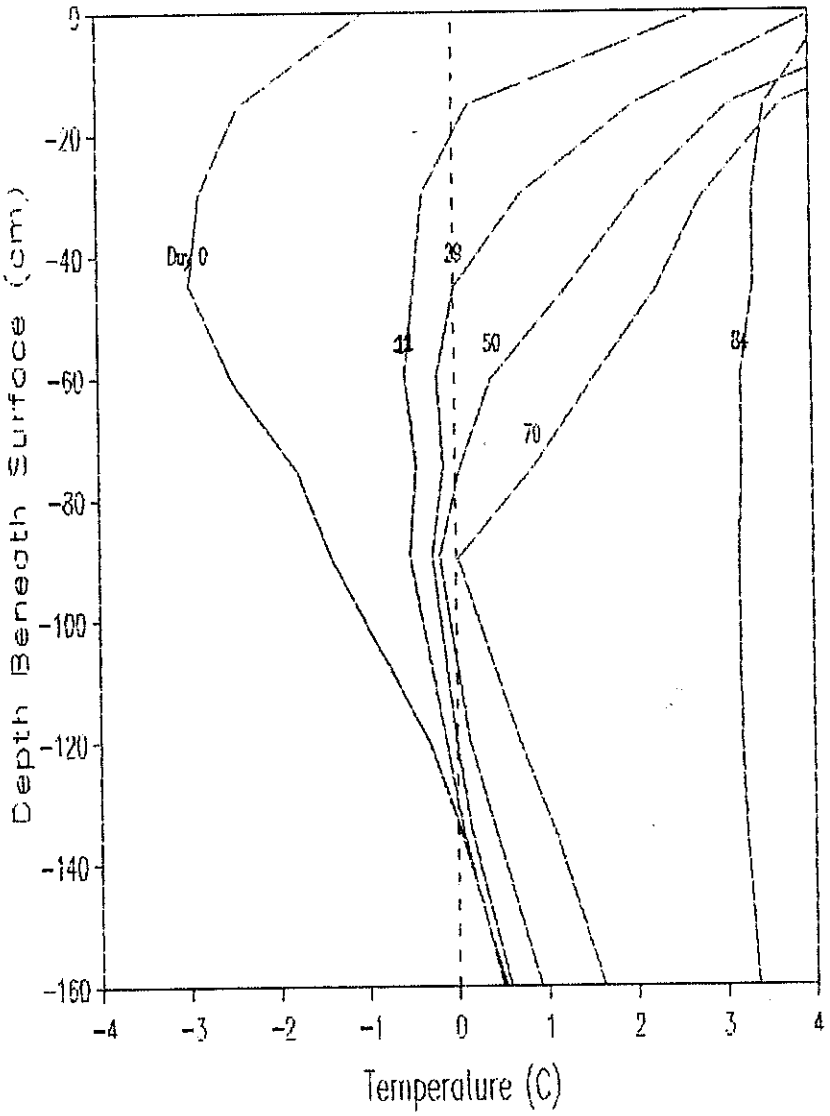


Figure 5.2 Pipe Shape During the Third Thaw

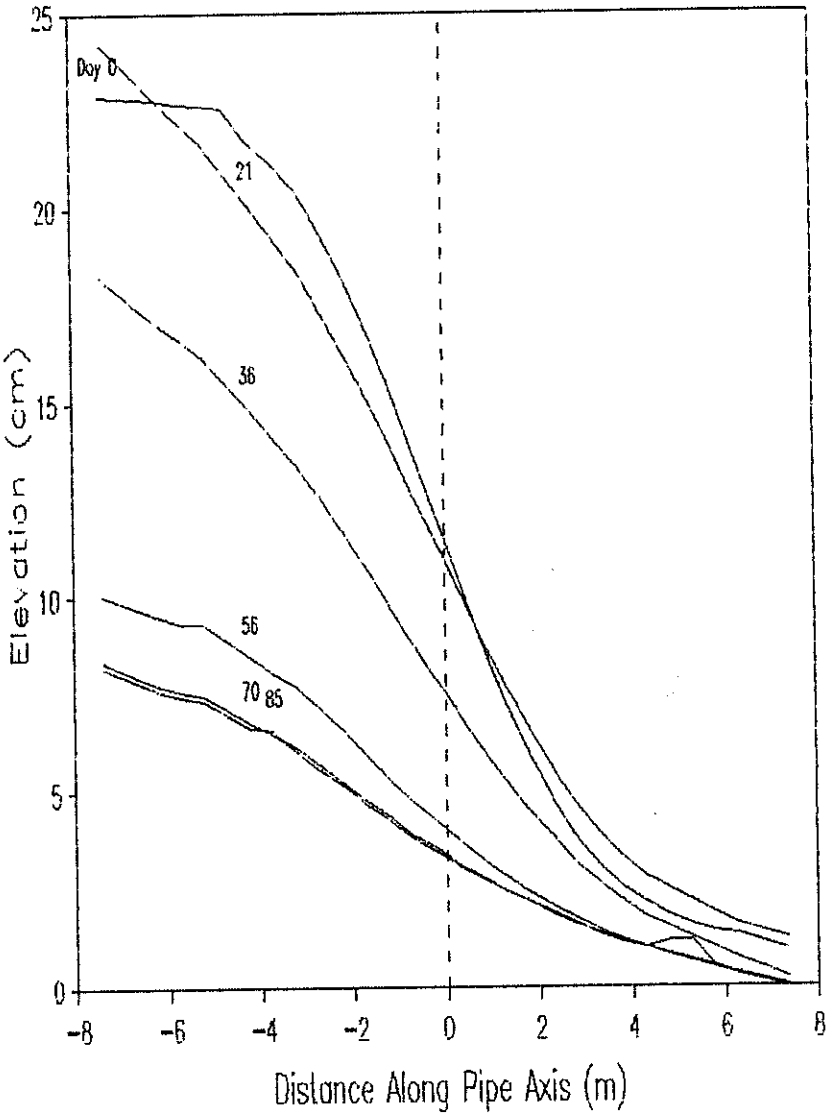


Figure 5.3 **Soil Pressure in the Sand Section, Third Thaw Observations from Glotzl Cells**

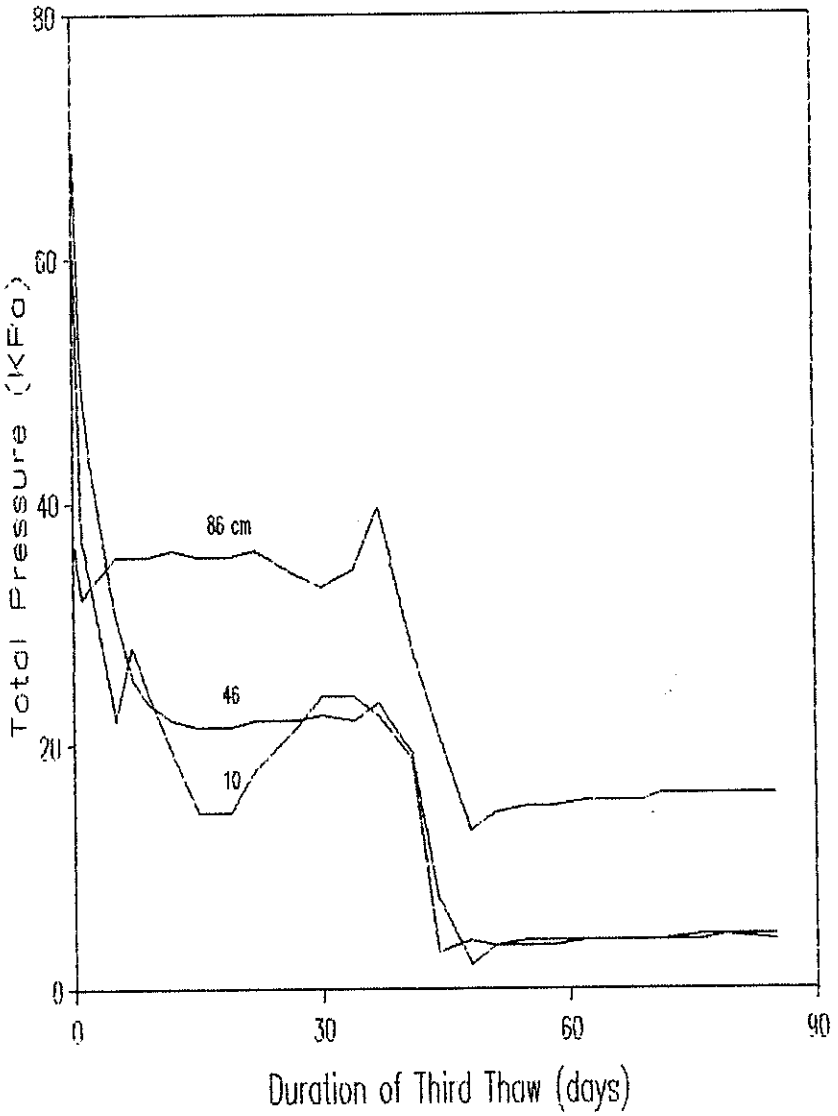
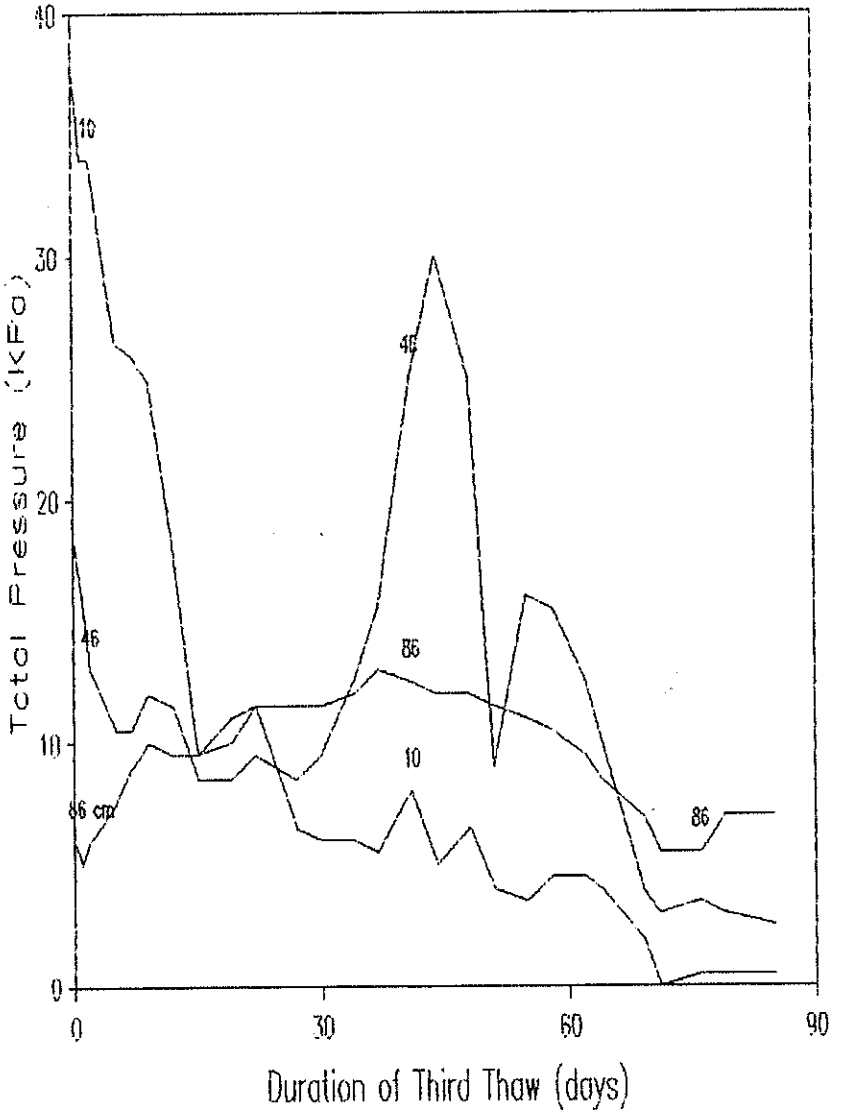


Figure 5.4 **Soil Pressure in the Silt Section, Third Thaw Observations from Glotzl Cells**



thaw periods. A database is being compiled to facilitate this task. The analysis will be used to guide necessary observations during the fourth thaw cycle.

The differential settlement pattern observed during the second thaw period is still being analysed and will be reported at a later date. Technical problems with the magnet heave device occurred during the second thaw resulting in an unfortunate loss of data. Also, the surface magnets for several of the sites did not settle uniformly with the soil surface because of repairs made to the access tubes. This resulted in the surface magnet being suspended above the ground surface making estimates of total settlement difficult. However, estimates of differential settlement will be made at various sites and the observed pattern will be viewed in light of the existing thermal conditions.

VI Summary of the Third Freeze Cycle

The major finding of this freeze cycle is that the magnitude of heave which occurs in already frozen ground is much greater than previously anticipated. Also, the thickness of frozen soil continuing to exhibit strain was quite large (as much as 60 cm at magnet heave site 4). The amount of strain observed in already frozen ground is the greatest when temperature gradients are small and the temperatures are close to the ice point.

For the Caen silt, strain in already frozen ground persisted to a measurable degree down to temperatures of -0.3 C. Strain was observed in soil layers colder than this but to a lesser degree. Had the experiment run longer, more strain may have been detected in these soil layers.

Efforts during the fourth freeze cycle will be directed to examining the differential strain patterns in more detail. Also, the pressure patterns evident during soil freezing will be examined in more detail. The Petur devices have been refurbished and more installation sites selected in close proximity to the areas where soil heave and temperature are measured. The magnet heave device has been refurbished and modifications have been made to the surface magnets so that the pattern of thaw settlement can be observed at the end of the fourth freeze cycle.

Complete details of re-instrumentation and preliminary observations of the fourth freeze cycle will be reported in a subsequent report. Current efforts are also being directed toward compiling the existing data base in a more efficient manner to permit a more detailed comparison of observations between the various freeze and thaw cycles.

VII Status of the Canada-France Project

7.1 General: Retrospective

The contract sum for the year being reported, was reduced at the request of the Scientific Authority, below that initially envisaged. In spite of efforts to maintain a full programme of observations, by April 1987 it was necessary to plan for a gap in operations following completion of thawing. It had been intended to continue observations of settlement and then to commence the fourth (current) freezing cycle in September. Instead the position of field project manager was left vacant for the period June to September, during which a very limited programme of observations and maintenance was carried out by French colleagues.

Some time was spent on developing procedures which during the remainder of the investigations, will allow a slightly larger proportion of the expenditures to be used for scientific analysis. Efforts were made to increase computer-handling of data thus substantially reducing the need for secretarial and drafting services in the preparation of reports.

7.2 General: Future Operations

The Canada-France pipeline-ground freezing experiment commmenced operating in September 1982 and has continued for five years. For comparison, the field experiments with pipeline test sections, initiated by Canadian Arctic Gas, at Calgary, were carried on over a ten-year period with the pipes being removed in 1985. The Calgary experiments were simpler in aim, primarily providing information on temperatures and surface heave. The present report further demonstrates the long periods necessary for such studies, not only because of the slow freezing process, but because of the complexity of the problem as progressively revealed by the observations and analyses.

The extent of secondary (continuing) frost heave has now been elucidated but the analysis of the internal pressures in the frozen annulus is difficult. Various modifications of apparatus have been necessary. The cumulative deformations of the soil, revealed by the surface contours, could be very important if pipelines are exposed to repeated seasonal freezing. To investigate this aspect, metre-long columns of stacked wooden discs have been inserted at sites around the pipe. Following thaw, it is intended to make excavations to observe the lateral displacements of these discs. A recent discovery which calls for investigation is the existence of a cavity of several centimeters immediately beneath the pipe, which apparently persists from one cycle to the next and along much of the pipe length in the silt section. More generally, and particularly from the point of view of pipeline design, there is a requirement for quantitative information for soils additional to those used in the current experiment.

A major requirement is for a person qualified in stress analysis to work in association with those engaged in the studies of the thermodynamics, in order to obtain a comprehensive picture of the stress development and consequent deformations in the ground as well as in the pipe.

A further important aspect is the successive changes in soil micromorphology which are believed responsible for the different results obtained in successive, otherwise similar freeze-thaw cycles. It is intended to pursue the studies of the micromorphological changes in the materials, using the frozen soil preservation technique developed recently (see last year's report) to prepare microscope slides.

Thus the project has become multifaceted and much more sophisticated than at the time of its conception. There remain many unanswered questions that

bear on the design of pipelines, and it is unfortunate that a significant reduction of the work seems necessary. Financial constraints have led to a situation where the Canadian contribution to the operating costs of the experiment leaves insufficient funds for the necessary research personnel for analyses of observations. This is extraordinarily unfortunate, considering the importance of the research to Northern development, and the fact that a sizable proportion of the costs are paid by the French anyway.

We currently envisage operating a much-reduced programme of experimentation after completion of thawing, at the end of 1988. This decision might be modified or reversed, if additional funding becomes available.

7.3 Industry Involvement in the Project

Through the seventies, when there were a number of megaprojects being promoted, there was a reluctance on the part of the pipeline industry to recognise the need for special research projects into the special conditions applying in regions of extensive ground freezing. By the end of the decade, these attitudes were changing, and millions were spent on field test facilities especially in Alaska. These expenditures were abruptly terminated with the decline in the gas market. The Canada-France project, the first of its kind and aimed at elucidating fundamental scientific questions, has not received significant funding from Canadian industry. During the year, however, a major Canadian company responded to our advertisement seeking industrial sponsorship of personnel. Discussion ensued and agreement in principle was established for a engineer skilled in stress analysis to be seconded to the project. This person would, of course, also facilitate direct company access to the research results. The appointment has, however not as yet materialied, as new business commitments in the company meant the person could not be released currently.

Another company, responsible for a major northern pipeline proposal, has also approached us for advice concerning the implications of the findings from the project. It became apparent in discussion, that complete answers to the company's concerns could not be provided although findings to date from the project were highly relevant. In a more favourable financial climate this company would sponsor the research.

The mathematical models developed by Michel Fremond, which predict the thermal, hydrological and mechanical conditions around the pipe, have reached a high degree of sophistication. They have found various applications in France. In order to introduce the techniques into Canada, a two-day seminar is being held at Carleton University in April. In recognition of the importance of such programmes to geotechnical design, and of the use of supercomputers to Canadian industry more generally, Cray Canada Inc. are co-sponsoring the seminar and providing all the required computing facilities, including access to the supercomputer.

7.4 Publications

To date, scientists associated with the project have published ten scientific articles in reviewed journals or conference proceedings. A further six articles were published, along with those of other contributors, in the Proceedings of the Caen Seminar 1985. There have been eight reports in similar format to the present one and copies are available at cost from the Geotechnical Science Laboratories and from Energy Mines and Resources, Canada. In addition there have been a number of internal reports and 4 theses based on the project. Other items referring to the project include a small book, and news reports in professional journals and newspapers. Finally an additional 3 - 4 scientific articles have been based in part on information deriving from the project, as have three more project reports.

A publications policy was agreed between the two countries' participants at an early stage of the project. This includes publication as early as reasonable of findings relating to an aspect of the project and which are mainly the responsibility of an individual (perhaps with associates) from one of the sponsoring countries. Publications (in journals) which report in detail on the scientific findings of the project as a whole are generally co-authored internationally, with the approval of the Scientific Committee. In this respect, it has been agreed that there will be a series of definitive papers on the project and a preliminary proposal for these to be carried in a prominent Canadian journal has been well received. However it is also agreed that these articles to be truly definitive must not be unduly liable to being contradicted by later findings. Accordingly their preparation will proceed as a number of the findings are confirmed and consolidated by the current freeze-thaw cycle.

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Appendix 1 Study of Internal Confinement During Shear of a Frozen Sand

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When determining the stability of a chilled pipeline embedded in an annulus of dense frozen sand, it is important to be able to evaluate the resistance against failure of that annulus. It has been postulated (Ladanyi, 1981, 1985) that a portion of shear strength of a dense frozen sand is due to the internal confinement resulting from the dilatancy hardening phenomenon.

When a dense granular material with a visco-plastic matrix, such as ice, is submitted to deviatoric stresses, its dilation during shear is opposed by ice bonds. The resulting tensile stresses in the pore ice are transfered to the sand grains, producing an increase of intergranular stresses in the sand skeleton. The strength increase of frozen sand due to this internally generated confinement is termed "dilatancy hardening".

The purpose of this study (Morel, 1987), was to check the validity of a theory, proposed by Ladanyi (1985), for determining the amount of the dilatancy hardening effect. For this purpose, two series of triaxial compression tests with volume change measurement were carried out on a uniform sand, at carefully controlled densities. In the first series, the sand was frozen and ice-saturated, while in the second, the same sand was tested unfrozen and water-saturated. In all the tests (23 on frozen sand and 16 on unfrozen sand), a close attention was given to the variation of the dilatancy rate as a function of the initial sand density and the confining pressure.

The test results show that the compression strength of the frozen sand observed in the tests agrees well with theoretical predictions. In fact, it is found that, as predicted, about a half of the measured uniaxial compression strength of a dense sand is actually due to the internal confinement, the rest being supplied by the shear strength of the pore ice. The concept holds, however, only as long as the ice bonds are in tension and unbroken, which happens at low confining pressures and at small shear strains, not exceeding about 1 to 2 percent. Clearly, a high confining pressure, preventing the sand to dilate, will also eliminate the internal confinement effect.

Another interesting finding resulting from these two series of tests, concerns the dilation rate at failure, which, in a frozen sand, was found to be much higher than in an unfrozen sand, at the same initial density (Figure 1). This may be explained by the fact that the observed overall dilation rate in an unfrozen sand is always a sum of local compressions and dilations of the sand skeleton, while, in a frozen sand, because of the presence of pore ice, only dilation can occur. A compression can take place in the latter only if the pore ice thaws under a high confining pressure.

Finally, in order to be able to better understand the phenomena associated with the shear of frozen granular materials, a two-dimensional model was constructed, using the well-known "rod material" principle. The model material, made of roughened cylindrical aluminium rods of two different diameters, was saturated and frozen. It was then submitted to biaxial compression tests (Figure 2) with vertical stress constant, and lateral stress decreasing. The tests have made it possible to inspect visually and record the behaviour of pore ice during shear deformation.

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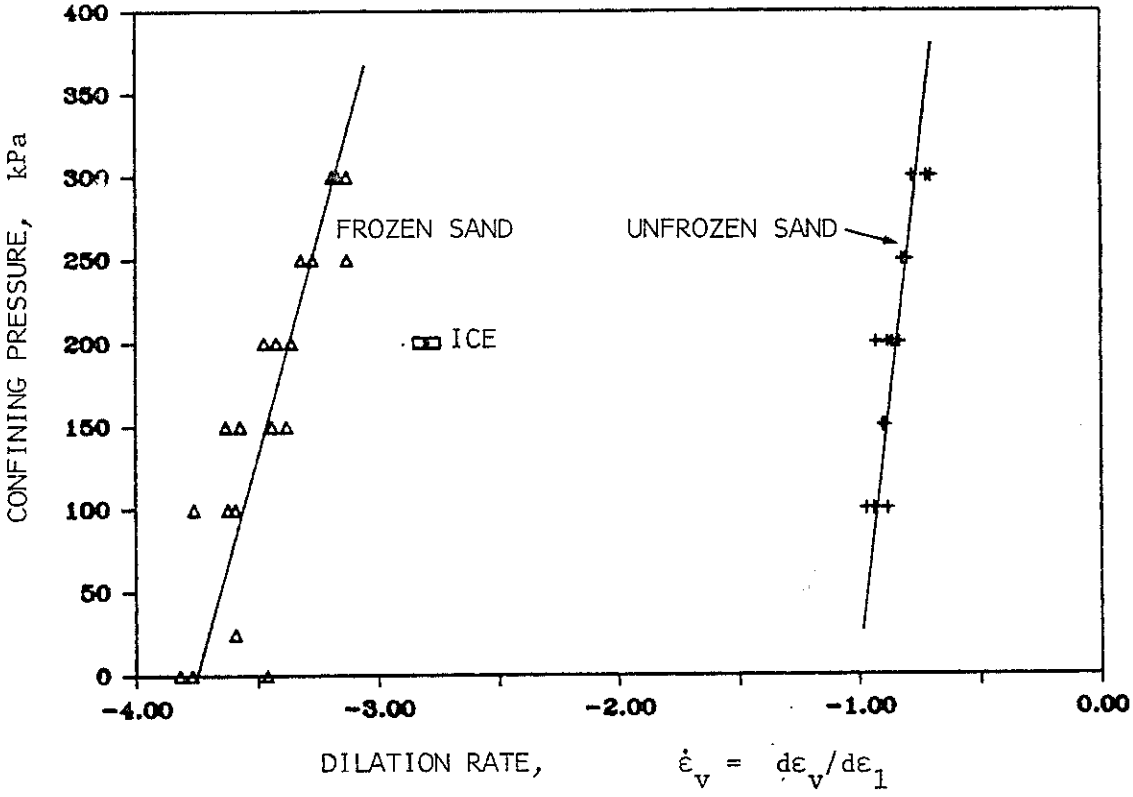

Figure 1. Dilation rate at failure in frozen and unfrozen sand.

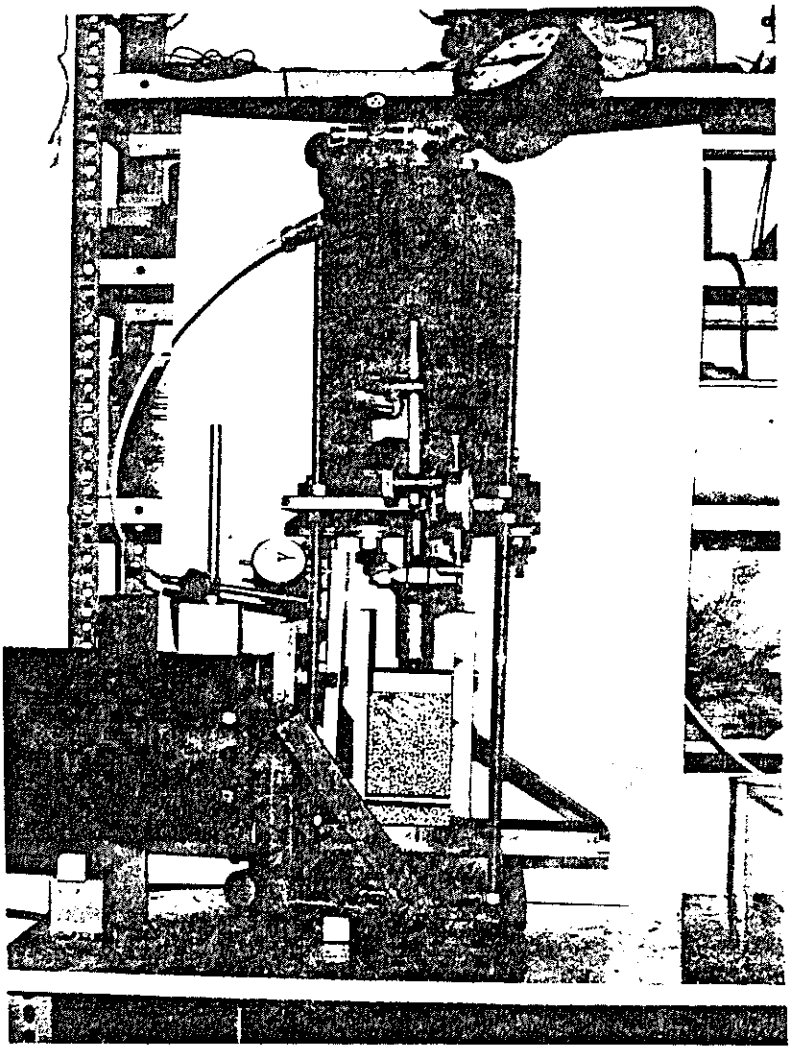

Figure 2. Test set-up for biaxial tests on ice-saturated rod material.