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ANALYSES OF STRESSES DEVELOPED IN PIPELINES BURIED IN FREEZING GROUND

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Abstract

Through a joint Canada/France research project conducted at the Centre de Geomorphologie, Caen the behaviour of buried pipelines subjected to negative temperature is under investigation. Summarised in this report are the experimental results from the first and second freeze cycles with an intervening thaw period. Among the parameters observed were the thermal regime, frost heave of the soils, pipe deformation and soil stresses. The facility tests were paralleled by laboratory testing of soil properties.

Résumé

Un projet de recherche Franco-Canadien, pour étudier le comportement d'un gazoduc enterré et soumis à des températures négatives, se déroule à la station expérimentale du Centre de Géomorphologie à Caen, en France. Ce rapport présente les résultats du premier cycle de gel (8 1/2 mois), du cycle de dégel qui suivit (4 mois) et du début d'un deuxième cycle de gel. On y résume sommairement les mesures du régime thermique, du soulèvement du au gel, de la déformation du pipeline, et des contraintes dans le sol et le tuyau. Les essais en laboratoire sur les propriétés des sols sont aussi discutés brièvement.

ANALYSES OF STRESSES DEVELOPED

IN PIPELINES BURIED IN FREEZING GROUND

for

EARTH PHYSICS BRANCH
ENERGY, MINES AND RESOURCES, CANADA

GEOTECHNICAL SCIENCE LABORATORIES
DEPARTMENT OF GEOGRAPHY
CARLETON UNIVERSITY
OTTAWA, ONTARIO
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DSS Contract Number: OSU82-00364

FOREWORD

The present document constitutes the final report under Contract No. OSU82-00364 Department of Supply and Services Canada (January 1, 1983 to December 31, 1983): "Analyses of stresses developed in pipelines buried in freezing ground", Principal Investigator P.J. Williams. This contract was carried out using facilities provided at the Centre de Geomorphologie, Caen, Normandy, through the joint France/Canada research project: "The behaviour of buried pipelines under negative temperatures". The continuing Canadian involvement in this joint project is based on contracts between the Geotechnical Science Laboratories, Carleton University and the Department of Supply and Services, the latest contract serial number being OSU83-00157: "Investigation of soil freezing in association with a buried chilled pipeline in a large scale test facility, phase 3", Principal Investigator P.J. Williams, Co-principal Investigator M.W. Smith. The present report concerns the second year of the study of stresses in a pipeline buried in soil undergoing freezing and thawing.

An interim report on the present study was included with the report "Investigation of soil freezing in association with a buried chilled pipeline in a large scale test facility, phase 2", dated August 1983. The reader is referred to this and earlier reports (see references) on the project for a fuller description of the experimental facility.

A thesis by M. Gilles Lemaire, for the Master's degree at Ecole Polytechnique, Montreal, has recently been completed, which reports a largely theoretical study of pipe stress and deformation in relation to frost heave. Material from this thesis will be included in future reports on the project. A further thesis is expected during the forthcoming year. The analyses of the findings described in the present document are expected to be substantially developed during the coming year.

This report has been largely prepared by Henry Crawford, Field Project Manager at Caen, July-November 1983 and by Scott Dallimore, with assistance by Doug Fisher, Field Project Manager November-March 1984. Professor W.H. Bowes, Department of Civil Engineering, Carleton University and Professor B. Ladanyi of Centre d'Ingenierie Nordique, Ecole Polytechnique, continue to be consultants to this project with reference to pipe behaviour and mechanical properties of frozen ground respectively.

The joint France/Canada research project involves a combined French and Canadian team of scientists, students and technicians. The project as a whole is supervised by a scientific committee and members affiliations indicate the institutions which are involved in the Memorandum of Agreement:

M. Jaime Aguirre-Puente, Laboratoire d'Aerothermique, Centre National de la Recherche Scientifique

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1. INTRODUCTION

1.1 General

This report presents an overview of the results of the second year (January 1, 1983 to December 31, 1983) of a study of stresses in a chilled pipeline buried in soils undergoing freezing and thawing conditions. The study is part of a joint Canada-France pipeline research project being undertaken in a large, temperature controlled facility in Caen, France.

The main part of the report consists of a detailed presentation of selected data collected during the various experimental periods of the study. A brief review of work undertaken prior to January 1, 1983 is included, as well as a description of the experimental and remedial work undertaken during 1983.

1.2 Background

When a chilled gas pipeline crosses a transition between two unfrozen soils of contrasting frost susceptibilities, differential heaving of the pipeline and the surrounding soil may occur. Determination of the interactions between the heaving soils and pipeline present unique design difficulties. It is important not only to understand the heaving characteristics of the soils but also the reaction of the annulus of frozen soil around the pipe, deformation of the pipeline and the state of stress in the pipe.

The project being undertaken in Caen is a multi-disciplinary study involving many aspects of soil freezing/thawing and the particular effects unique to soil freezing associated with a buried chilled pipeline. The investigation of stresses developed in a pipeline, and the complex physical interactions which occur when a chilled pipeline traverses two soils of different frost susceptibilities, represents an integral part of this study.

The main focus of the Caen project is to undertake a full scale experiment with precise control of the physical, thermal and hydrologic variables. The experiment does not attempt to model any particular field situation or pipeline foundation design. It attempts only to produce the types of conditions necessary for a fundamental study of the relations of frost heave of chilled pipelines to various factors, including the relation of pipe behaviour to the frost heave phenomena.

2. EXPERIMENTAL CONDITIONS

2.1 Test Facility

The experiment is being carried out at the "station de gel" at the Centre de Geomorphologie, Caen, France. For a detailed description of the test facility and initial set-up of the experiment the reader is referred to an earlier report by Burgess et al (1982).

The facility consists of a refrigerated hall 18m long by 8m wide with adjacent rooms to accomodate instrumentation and mechanical equipment. The base or trough of the hall has been specially prepared for the experiment in order to isolate the thermal and hydraulic regime and to carefully control experimental conditions. As shown on Figures 1.1 and 1.2 two different soil types, a non-frost susceptible sand and a frost susceptible silt, have been placed on each half of the trough. A 18m long, 273mm diameter steel pipeline with an independent refrigeration system was buried in the soils at an invert elevation of 30cm below the surface.

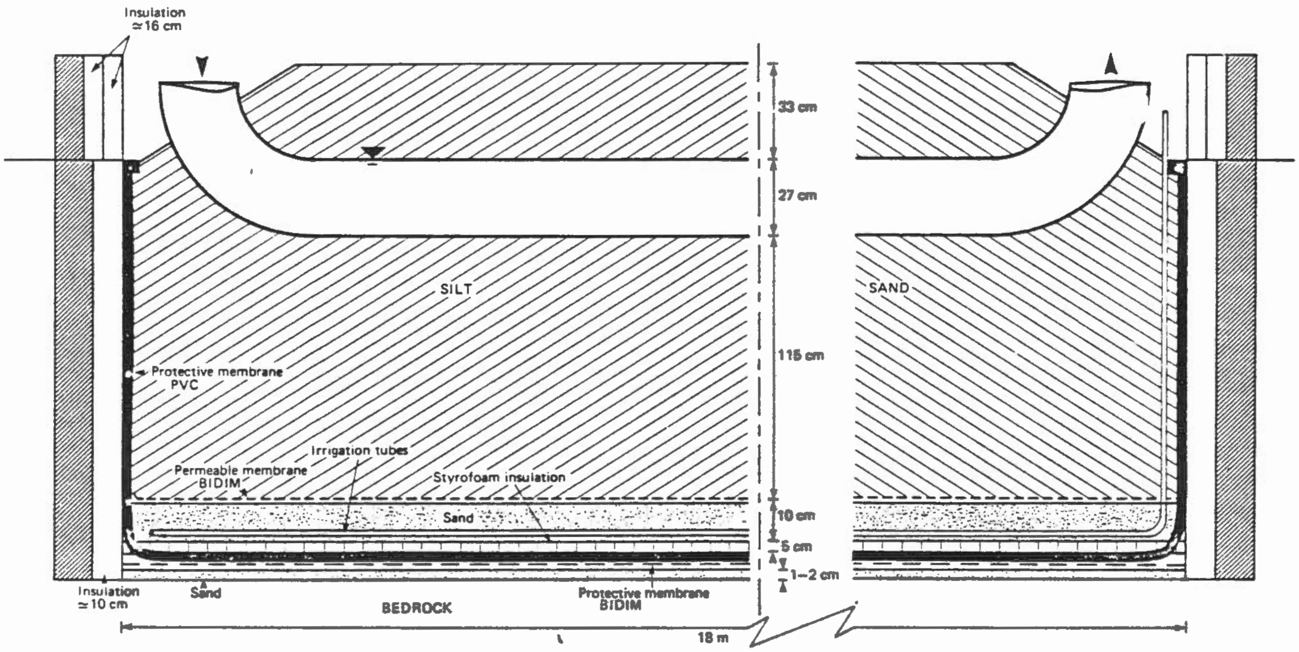

FIGURE 2.1 LONGITUDINAL SECTION OF TROUGH

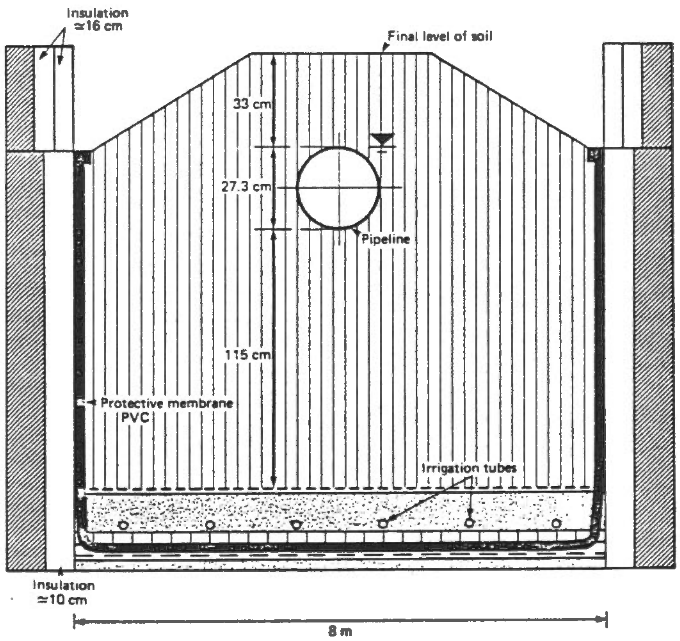

FIGURE 2.2 CROSS SECTION OF TROUGH

2.2 Instrumentation

The experiment is heavily instrumented and a large number of readings are taken on a regular schedule (see Geotechnical Science Laboratories, 1983). Table 1 presents an outline of the main types of instruments and a summary of the frequency of readings. Included are thermocouples and heat flux meters monitored automatically with a data acquisition unit. Also, regular measurements are taken manually of thermistors, water levels, surface levelling, tensionmeters, pressure cells, telescopic heave tubes, frost depth tubes, TDR moisture content probes, pipe deflection, pipe curvature and pipe strain. Periodic measurements not shown on Table 1 include temperature soundings, soil density profiling and gravimetric water content determinations. Where possible all data is entered into a micro-computer on site. It is then transferred onto a magnetic tape which is sent to Canada for detailed analysis.

2.3 Operating Conditions

The first freeze period (see Timetable) began on September 21, 1982 after preparation of the facility, installation of the instrumentation, stabilization of ground water levels and cooling of the two soils. The operating conditions during the freeze period called for an ambient air temperature in the hall of $-0.75^{\circ}C$ and an average pipe temperature of $-2^{\circ}C$. The water table was regulated at an approximate depth of 90cm below the original ground surface (initially the water table had been maintained at 60cm depth but due to excessive heave of the pipe and only limited frost penetration, after 3 months it was lowered to 90cm depth). The first freeze period continued for 8½ months until June 8, 1983.

Regime	Type of Sensor or Measurement	Number	Frequency of Readings	Comments
Thermal	Thermocouples (Iron/Constantan)	Approx. 160	every 4 hours	Read automatically by Solartron Orion data-logging system.
	Heat Flux Plates	5	every 4 hours	Read by same system as thermocouples.
	Thermistors	25	3 times per week	
	Frost Tubes	5	3 times per week	Indicate frost depth by colour change of organic dye.
Hydrologic	Piezometers	12	every day	Periodically supplemented by readings in 6 control wells.
	Tensiometers	20	3 times per week	
	Addition/removal of water		every day	Collected and measured defrost water from each of the three room ventilators and the pipe. Also recorded volume of water added at or pumped from base of pit.
	Time Domain Reflectometry (TDR)	28 horizontal 6 vertical	once per week	Electromagnetic measurement of volumetric unfrozen water content.
Pipe Deformation	Levelling (rods on pipe)	29 rods	once per week	Optical surveying.
	Rotation (rods on pipe)	29 rods	once per week	Angle measurement
	Curvature (rods on pipe)	24 points (3 rods each)	once per week	"curvature gauge" using finite difference approximation
	Strain guages	22 pairs (half-bridge) 2 rosettes (3 guages each)	2 times per week	Half bridge measures flexional strain only. Rosettes measure all strain components.

TABLE 1 INSTRUMENTATION SCHEME

Regime	Type of Sensor or Measurement	Number	Frequency of Readings	Comments
Physical Soil Parameters	Levelling (points on surface)	226 points	Axis and 2 cross-sections once per week. All points once per month.	All points referenced to fixed outside datum.
	Telescoping Tubes (Soil Heave)	38 in 4 sets	Once per week.	Nested tubes of various length, indicate relative movement of soil layers.
	Glotzl Earth Pressure Cells	15	3 times per week	
	Gamma Ray Probes	8 profiles in 2 cross-sections	Approx. every 4 months	Only 3 sets of measurements done to date. Gives profiles of total soil density. Buried PVC discs provide markers for soil heave estimation.

N.B. For a detailed description of sensor placement and measurement devices, see Burgess et al (1982) and Dallimore et al (1982).
The frequency of reading given here is typical over most of the duration of the experiment. Readings were taken more frequently during the first few weeks of freezing in September and October, 1982, and during the first few weeks of thaw in June, 1983.

TABLE 1 INSTRUMENTATION SCHEME (CONT'D)

TIMETABLE

Event	Designation in Report	Date
Memorandum of Agreement signed		Dec. 31, 1981
Completion of construction and testing		Sept. 21, 1982
START UP		
air/ground surface temp. $-0.75^{\circ}C$ pipe temp. $-2^{\circ}C$	FIRST FREEZE PERIOD	Sept. 21, 1982 June 8, 1983
temperature of air/ground surface raised to $+4^{\circ}C$ pipe temp. $-2^{\circ}C$	SURFACE THAW PERIOD	June 8, 1983 Oct. 17, 1983
temperature of air/ground surface lowered to $-0.75^{\circ}C$ temperature of pipe lowered to $-5^{\circ}C$	SECOND FREEZE PERIOD	Oct. 17, 1983 ?Summer, 1984?

A period of thawing of the ground surface commenced immediately after the first freeze period and continued for 4 months until October 1983. During this phase the pipe temperature and the water table were maintained as before, but the ambient air temperature in the hall was raised to +1°C and one day later to +4°C.

After several modifications to instrumentation and soil materials at the end of the thaw period a second freeze period was begun on October 17, 1983. The operating conditions are similar to the first freeze period except that the average temperature of the pipe was reduced to -5°C to increase the depth of frost penetration. The air temperature of the hall was set at -0.75°C and the ground water table was maintained at 30cm below the ground surface.

2.4 Modifications Made Prior to Commencement of Second Freeze Period

2.4.1 Instrumentation

There were unexpected diurnal variations in the temperature measurements during the first year of operation of the experiment (see Geotechnical Science Laboratories, 1983). Investigation during the summer of 1983 revealed that these variations did not reflect real temperature fluctuations in the soil but rather were inherent to diurnal changes in temperature of the data acquisition unit. To rectify this problem, prior to the initiation of the second freeze period, all thermocouples were re-wired to an external 0°C reference junction. This was accomplished without disturbing the thermocouple sensors located in the soil. Once this rewiring was completed an immediate change of up to 0.5°C in the temperature readings was noted. To further improve the stability of the temperature measurements, an additional thermostatically controlled electric heater was installed in the instrumentation room to reduce daily temperature fluctuations.

Due to the aforementioned problems, the expected accuracy of much of the temperature data from the first freeze period and the thaw period was not realized. This has been significantly improved for the second freeze period.

Prior to the second freeze period two additional frost depth indicators (see Burgess et al, 1982 for description of operation) were installed. These have been located away from the influence of the pipe, one in the sand and one in the silt.

During the course of the thaw period occasional small but abrupt changes in the water table occurred. It was speculated that a small leak may have developed in the external membrane and these changes may have corresponded to changes in the external natural ground water table. To investigate this, a pluviometer has been installed outside the chamber to monitor rainfall. In addition, periodic measurements of the natural ground water table will be made using an existing shallow well point which is located next to the testing laboratory.

2.4.2 Mechanical

Prior to the second freeze period, significant improvements were made to the refrigeration system of the pipe. During the implementation of these modifications care was taken to ensure that continuous down time of the pipe cooling system was never more than 2 or 3 hours, so as to minimize any detrimental effect on the experiment.

With the previous pipe temperature control system the temperature sensor for the pipe was located at the heat exchanger which was non-symmetrically located along the above-ground portion of the pipe. This meant that depending upon the direction of air circulation within the pipe, the air temperature at the input end of the buried pipe would vary due to unequal heat gain from the atmosphere in the hall. This effect became more pronounced during the thaw cycle when the temperature differential between the ambient air temperature and the pipe temperature increased. It was recognized that this problem would become more significant during the second freeze period with the reduced pipe temperature.

Two measures were taken to rectify the problem. Firstly, additional insulation was added to the above-ground portion of the pipe to reduce heat gain. Secondly, temperature sensors to regulate the pipe temperature were installed at each end of the pipe such that the input air temperature is constant regardless of the direction of air circulation.

During the warm summer months of July and August the pipe cooling system was operating near its maximum capacity and on occasion it would overload and shut down, particularly just after a defrost cycle. These shut downs required manual re-starting and hence if they occurred during the night, the shut down would be for several hours. To ameliorate this problem an additional radiator was installed in series with the existing radiator on the pipe compressor unit. Also, the efficiency of the defrost system was improved to reduce the duration of the necessary defrost cycles.

2.4.3 Soil Conditions

During the first freeze period a small fissure developed in the silt longitudinally above the pipe. During the subsequent thaw period the width of this fissure increased as the adjacent ground settled. The fissure had a maximum width in the order of 30mm and appeared to extend down to the top of the pipe. Concern was expressed that this crack might lead to the formation of an unrealistic "frost wedge" above the pipe during the subsequent re-freeze. Also, a few of the PVC sleeves which served to protect the vertical steel measurement rods on the pipe had been deflected and were obstructing the movement of the rods.

To remedy these effects the upper 150mm of silt immediately above the pipe was reworked and recompacted to a uniform density by hand tampers. Near surface instrumentation was relaid in this zone and the final ground surface was re-surveyed.

3. EXPERIMENTAL OBSERVATIONS - FIRST FREEZE PERIOD

3.1 Thermal Regime

The analysis of the thermal regime during the course of the first freeze period was complicated by the already-noted unreliability of some of the temperature measurements as recorded by the data acquisition system. The figures relating to the thermal regime represent the best estimate from all of the available thermal data. The accuracy of individual temperature measurements was found to be only about $\pm$ 0.25°C.

Figures 3.1 and 3.2 present the changes in the thermal gradients beneath the centre line of the pipe during the first freeze period. Although isothermal conditions near 0°C were desired at the start, time constraints limited the cooling of the two soils. As shown on the figures for September 22, 1982, the temperatures in the two soils were slightly warmer than desired, with the silt being warmer than the sand. The progression of the 0°C isotherm beneath the centre line of the pipe in the sand and the silt is shown as Figure 3.3. This figure shows the relatively slow progression

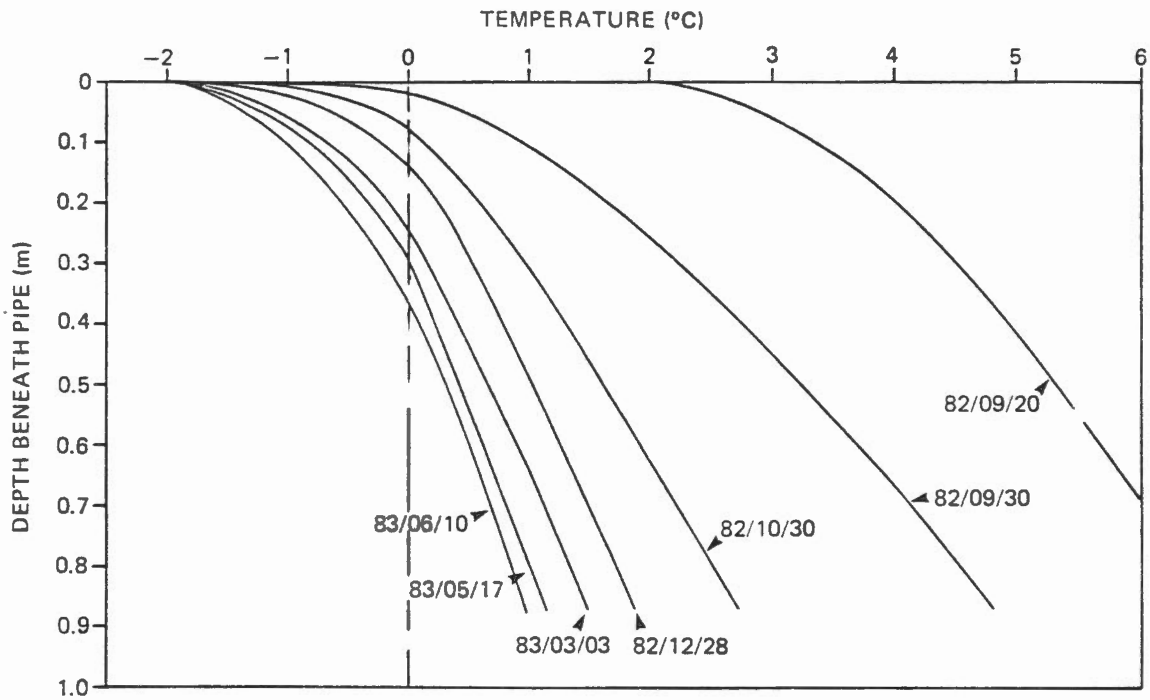

FIGURE 3.1 GENERALIZED TEMPERATURE PROFILES BENEATH CENTRELINE OF PIPE DURING FIRST FREEZE PERIOD. SILT SECTION BB.

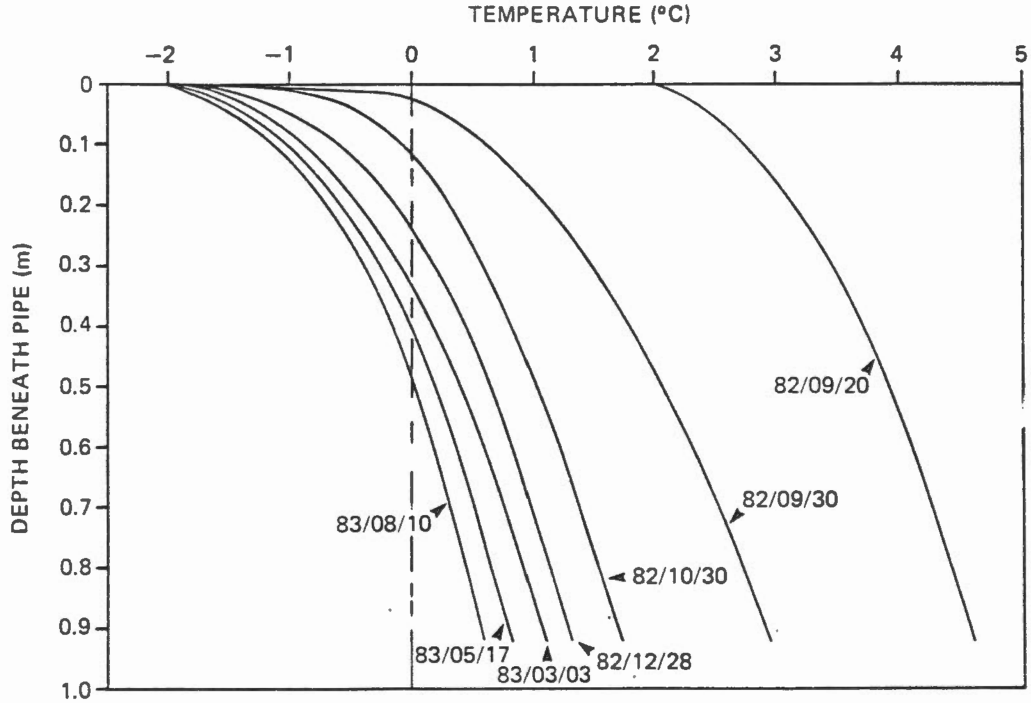

FIGURE 3.2 GENERALIZED TEMPERATURE PROFILES BENEATH CENTRELINE OF PIPE DURING FIRST FREEZE PERIOD. SAND SECTION AA.

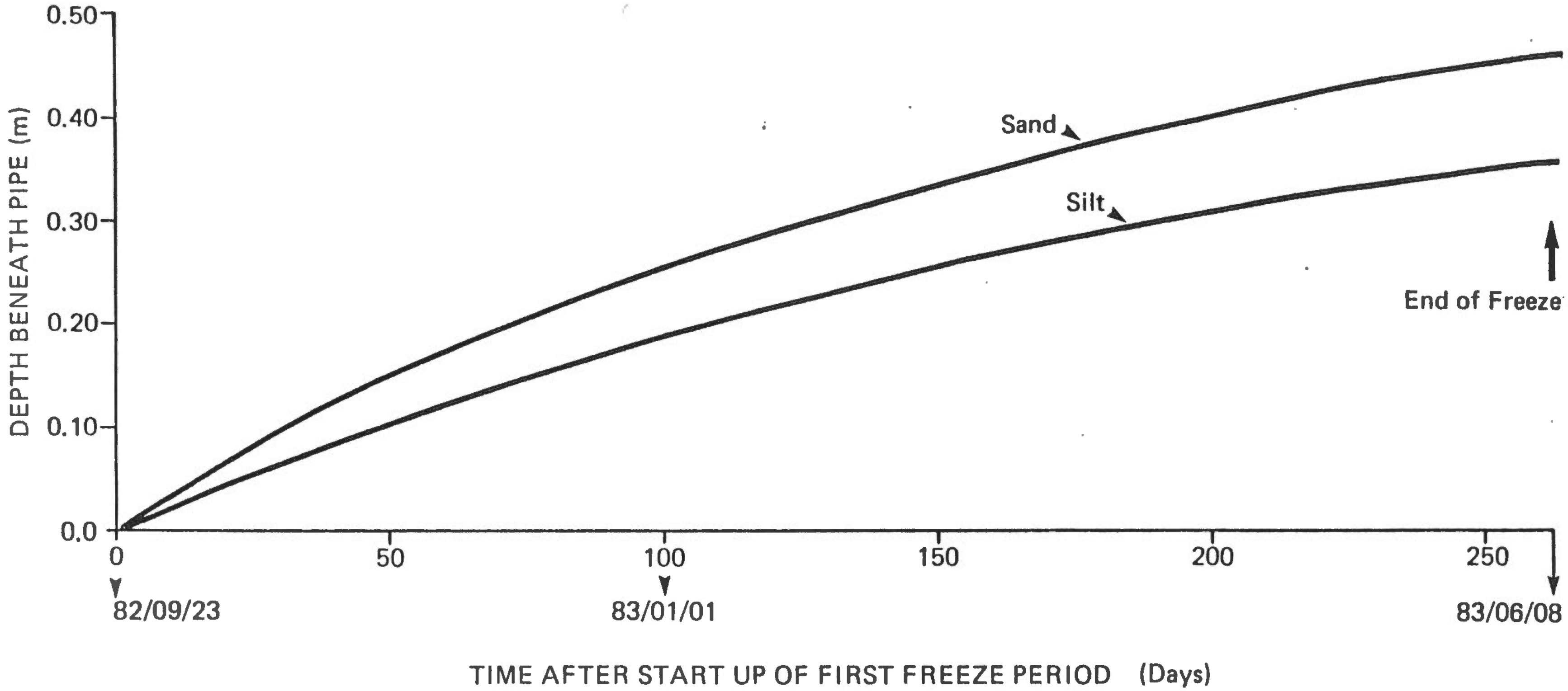

FIGURE 3.3 EVOLUTION OF FROST FRONT BENEATH CENTRELINE OF PIPE DURING FIRST FREEZE PERIOD

in the silt and the more rapid progression in the sand.

3.2 Pipe Deformation

Deformation of the pipeline began during the initial weeks of the first freeze period when differential heave between the silt and the sand began to occur. As shown on Figure 3.4, the pipe was displaced upwards in both soils with pipe deformation occurring in the transition zone between the two soils.

Determination of the state of stress within the pipe has been carried out according to the procedure outlined in the report, Geotechnical Science Laboratories, 1982. Build up of stress within the pipe is shown at four periods during the freeze period on Figure 3.5. It is estimated that a maximum stress of about 115 MPa approximately 50% of the yield stress was present in the pipe near the end of the first freeze period. Preliminary analysis and modelling of pipe stress distribution during the first freeze period has been undertaken in a M.Sc. thesis completed at Ecole Polytechnique in Montreal (Lemaire, 1983).

3.3 Frost Heave of Soils

The relative movement of the surface of the two soils during the first freeze period has been shown on Figures 3.6 - 3.8 which are a series of surface contour maps indicating net heave. These plots illustrate the undulating nature of much of the surface of both soils and the roughly symmetrical heave over the pipeline axis.

Observations with the telescopic heave tubes show these have worked satisfactorily and the observed heaves are in accordance with frost penetrations depths. Since the maximum frost penetration in the silt was

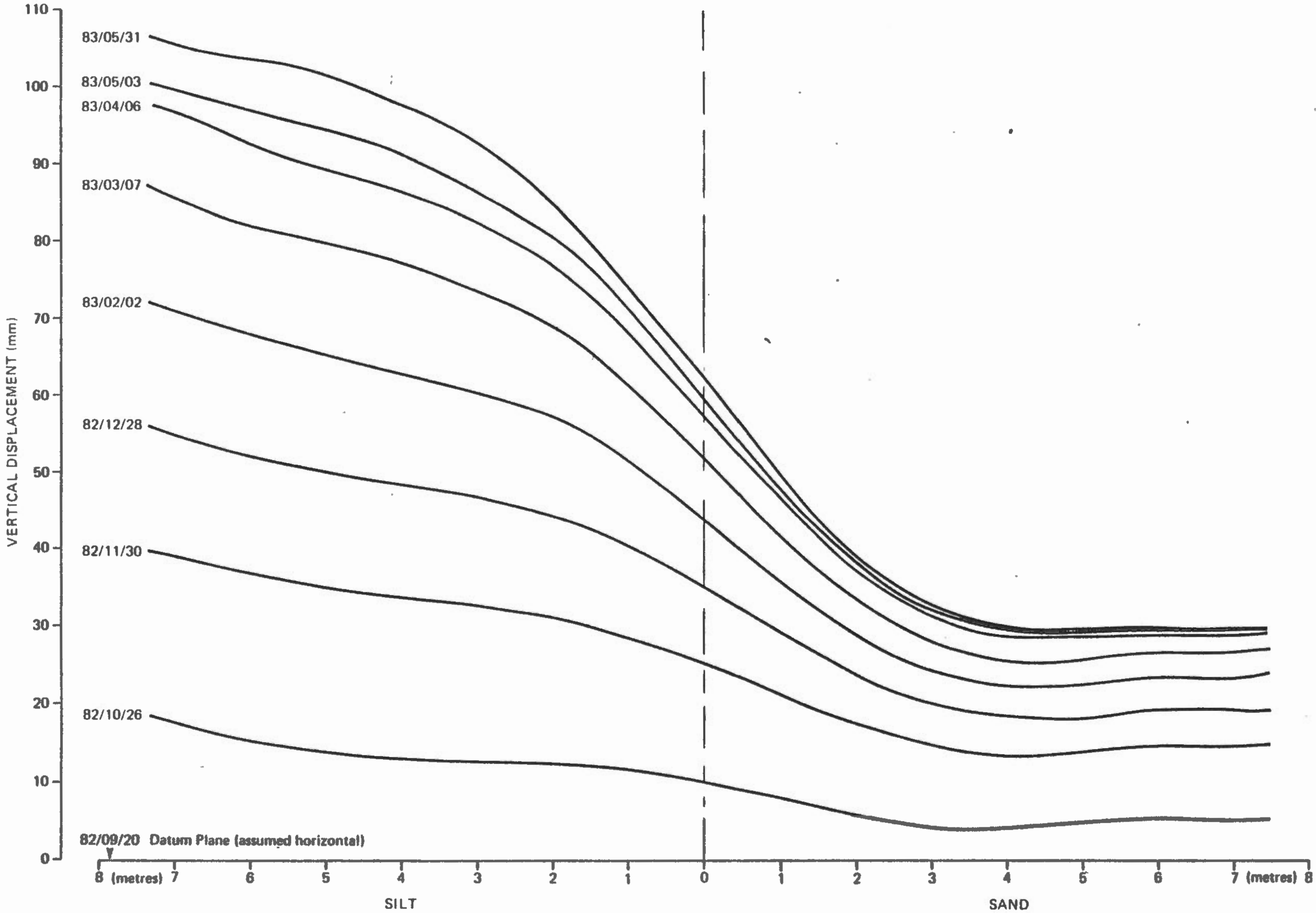

FIGURE 3.4 DEFORMATION OF PIPE AS MEASURED BY DISPLACEMENT OF RODS FIXED ON AXIS OF PIPELINE FROM 82/09/20 TO 83/06/07

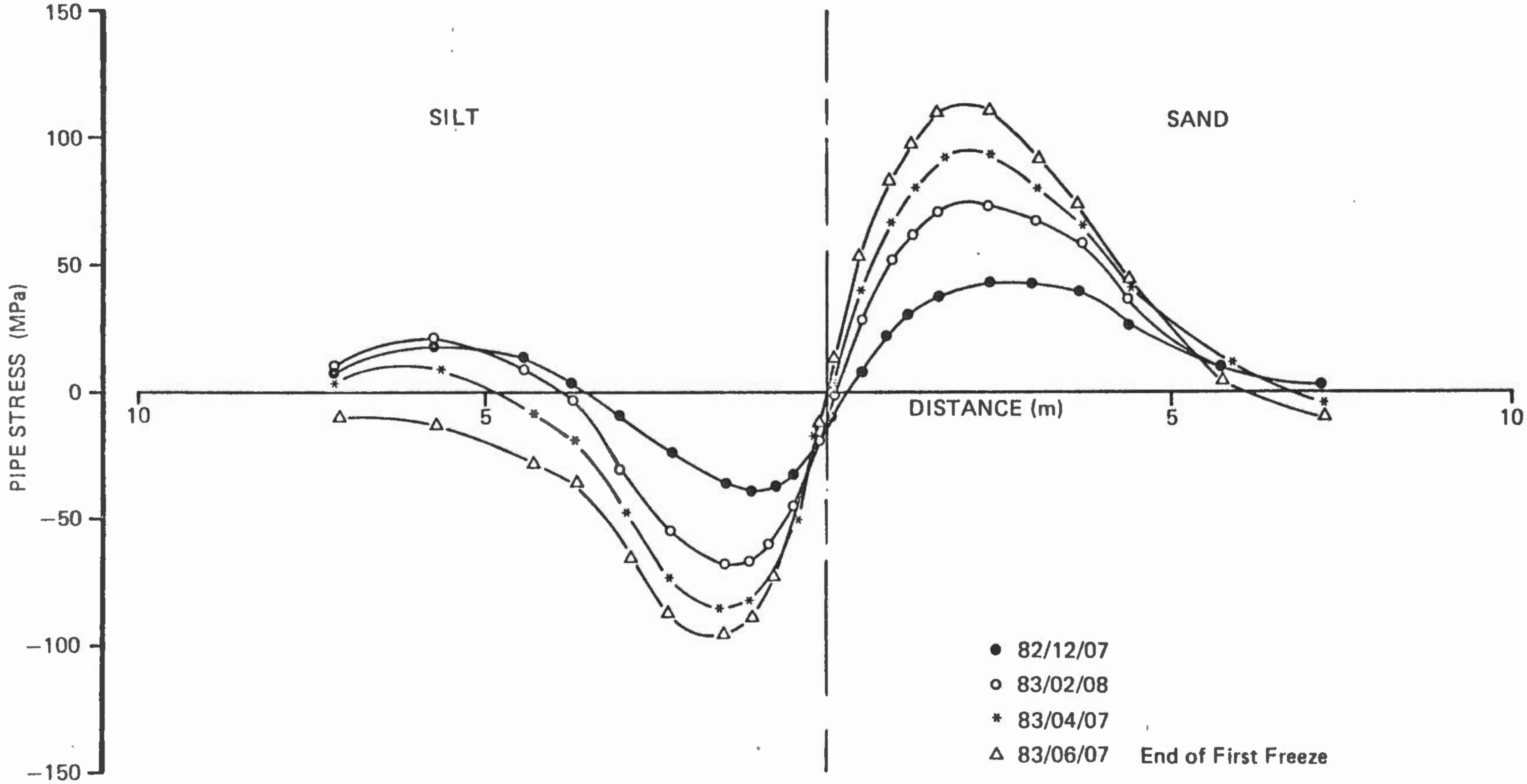

FIGURE 3.5 DISTRIBUTION OF BENDING STRESS IN PIPE DURING FIRS. FREEZE PERIOD
(Computed from strain gauge readings)

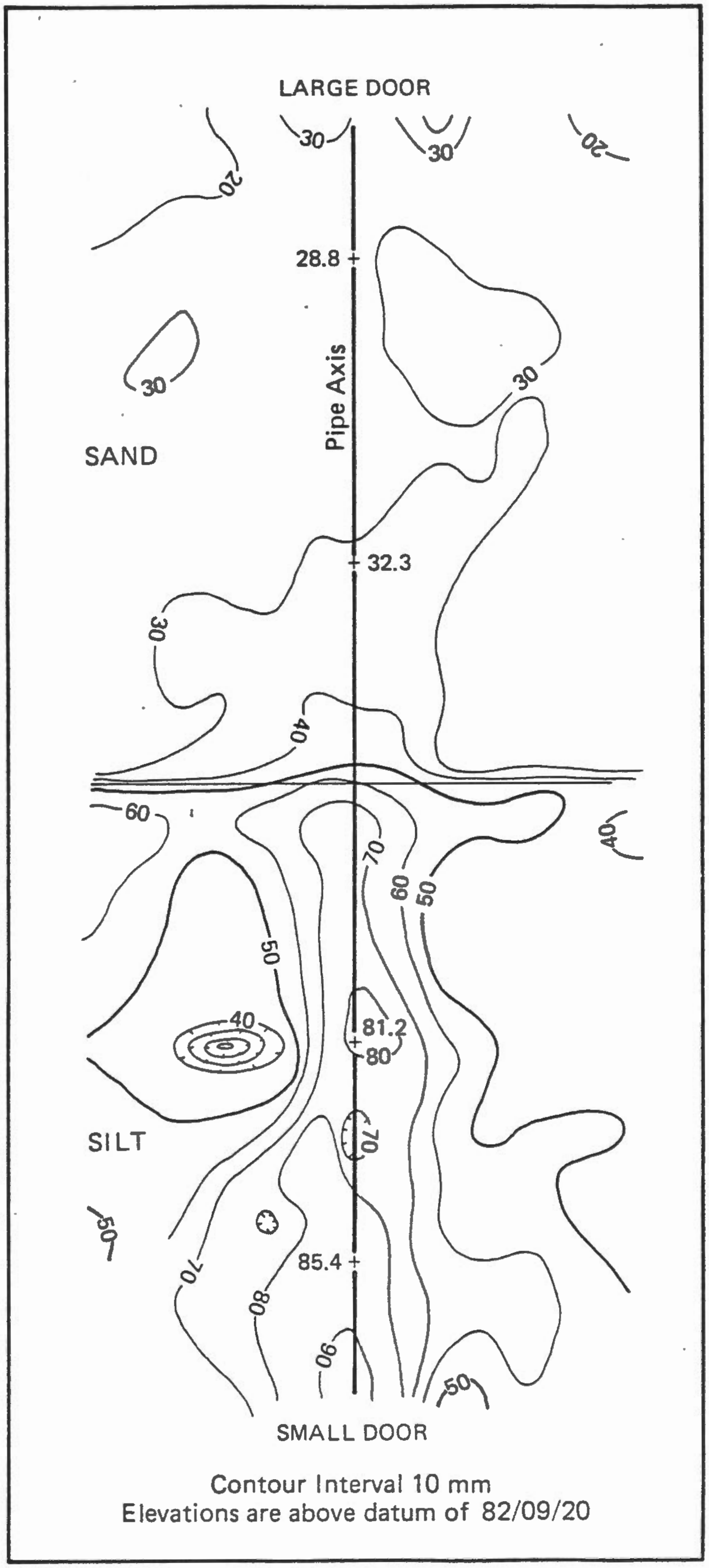

FIGURE 3.6 ELEVATION OF SOIL SURFACE, 83/01/05

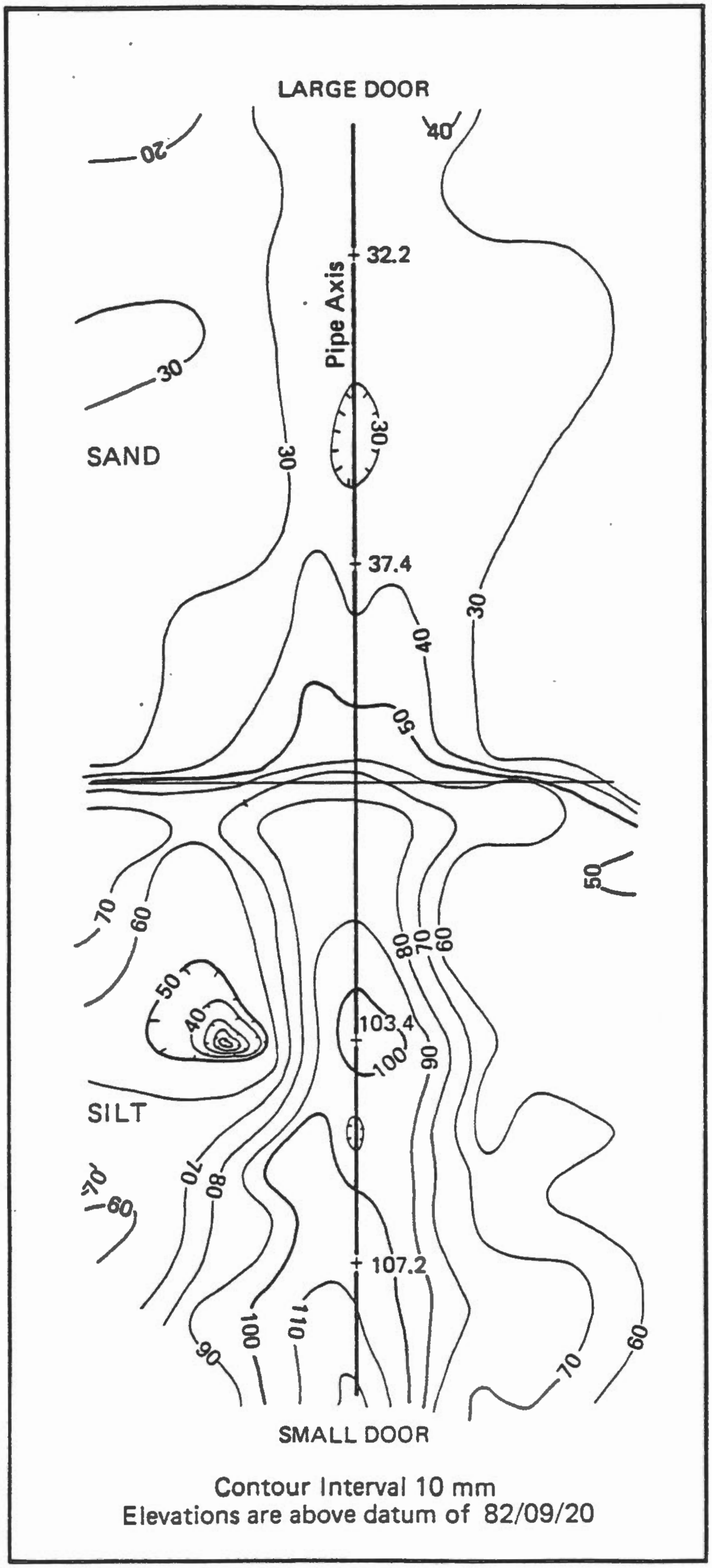

FIGURE 3.7 ELEVATION OF SOIL SURFACE, 83/03/08

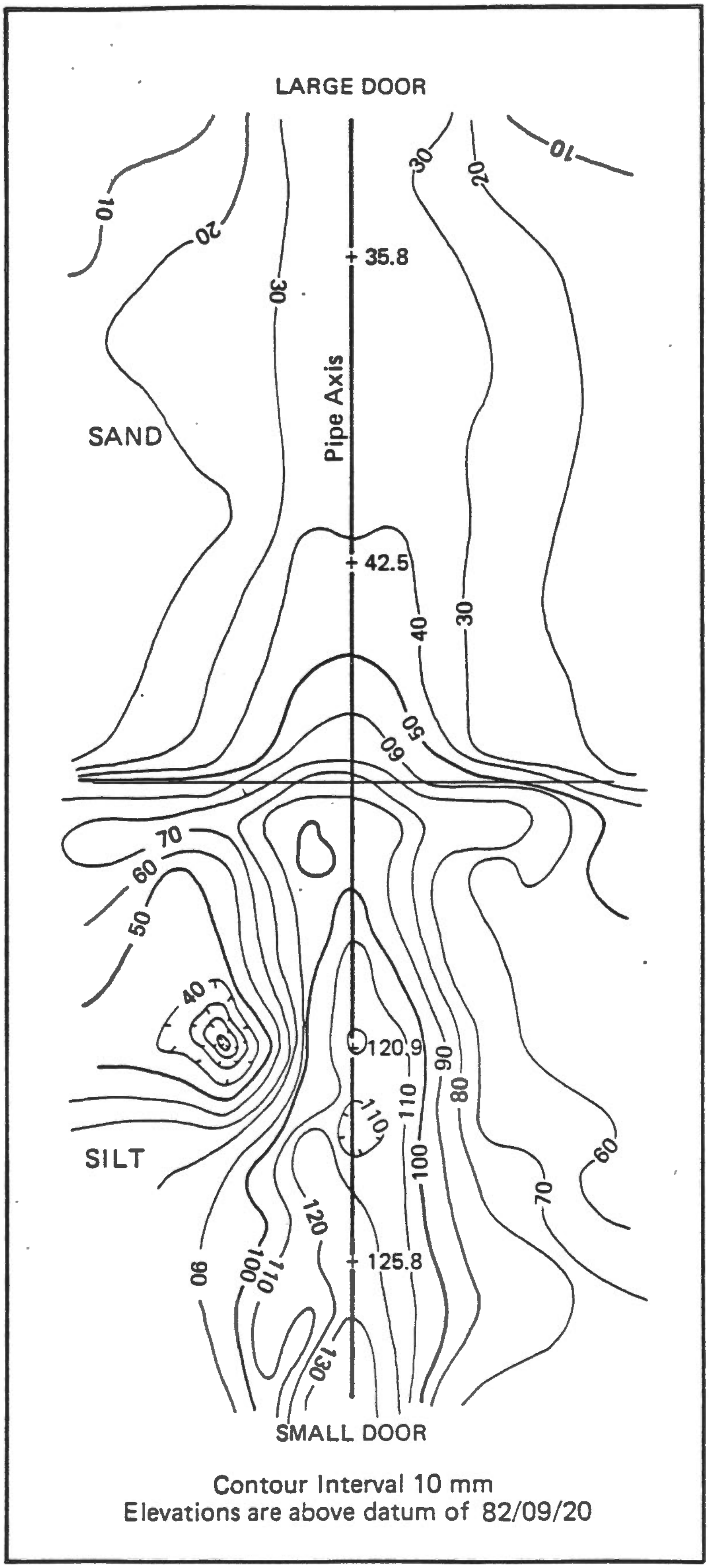

FIGURE 3.8 ELEVATION OF SOIL SURFACE, 83/06/07
END OF FIRST FREEZE PERIOD

only about 35cm, relatively few of the observations can be used to interpret possible strain of already frozen ground.

3.4 Total Stress Induced in Soil

A series of Glotzl pressure cells have permitted monitoring of the total stress state in the soil in the vicinity of the pipe. Figures 3.9 and 3.10 show the evolution of the vertical component of the total stress as measured by 6 cells located initially 46cm below the pipe. In each figure the initial stress state prior to freezing is shown with the change in stress indicated by the hatched area above or below the solid line. The relevant pipe profile has been superimposed to assist in interpretation.

Ideally the initial stress state beneath the pipe prior to freezing should reflect only the overburden pressure and should be uniform along the pipe axis, with a possible minor variation due to differences in the total unit weights of the sand and silt. In fact, the initial values are scattered somewhat, particularly in the sand. This can be attributed to instrument variation or possibly to small flexural stresses in the pipe which developed during the pipe installation. The average total stress measured beneath the pipe agrees well with the calculated overburden pressure.

Once the freezing began around the pipe the soil pressures beneath the pipe progressively changed to that of Figure 3.10. It is apparent that the maximum heaving pressure in the silt was not measured by any of the Glotzl cells but rather must have occurred just next to the sand-silt interface as shown in the figure. Similarly a decrease in total stress would have occurred in the adjacent sand. The corresponding increase and decrease in total stress beneath the pipe at the sand and silt ends respectively can be attributed to the flexural stiffness of the steel pipe.

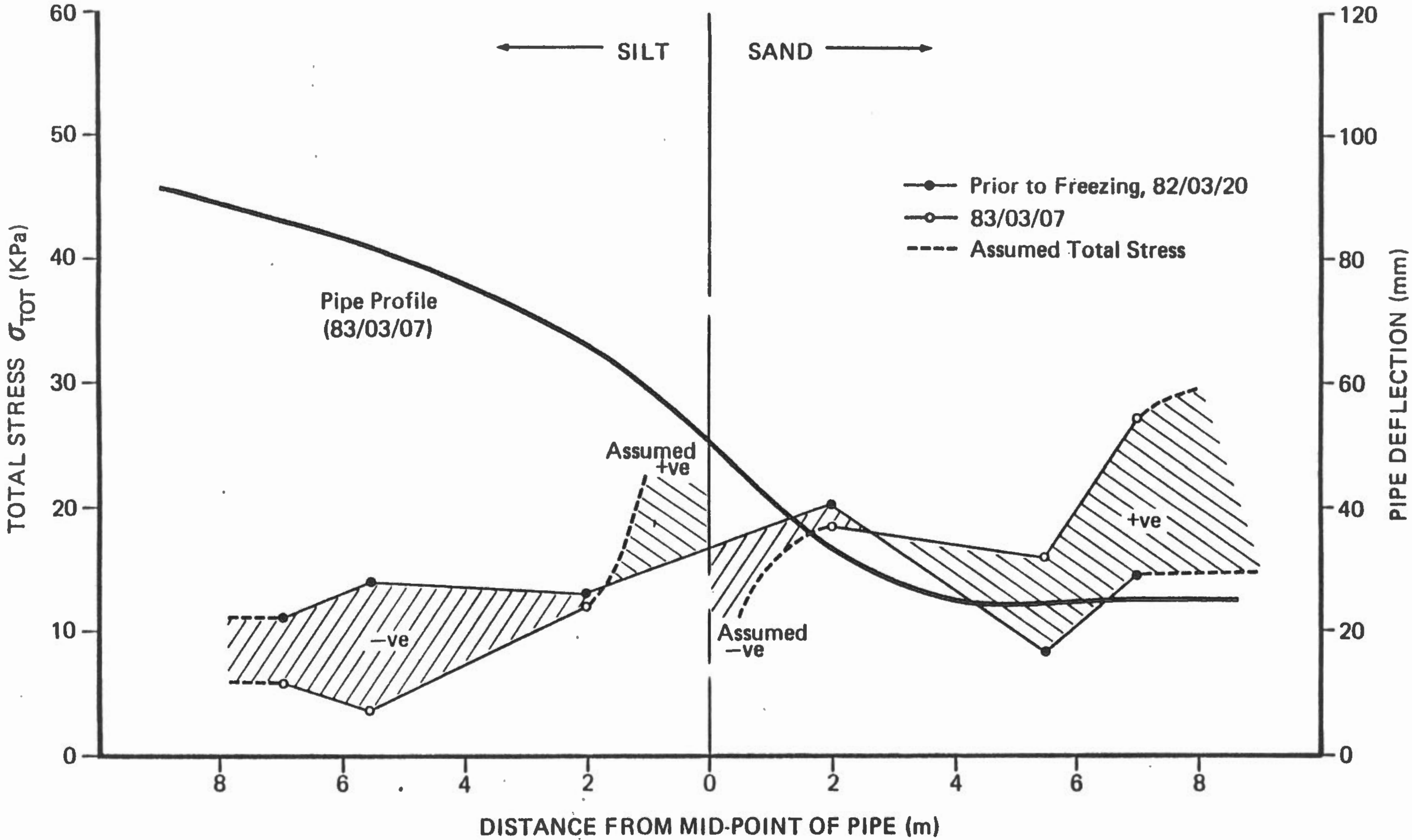

FIGURE 3.9 TOTAL STRESS IN SOIL BENEATH PIPE DURING FIRST FREEZE PERIOD (83/03/07)
(Pressure cells located initially 46cm beneath pipe)

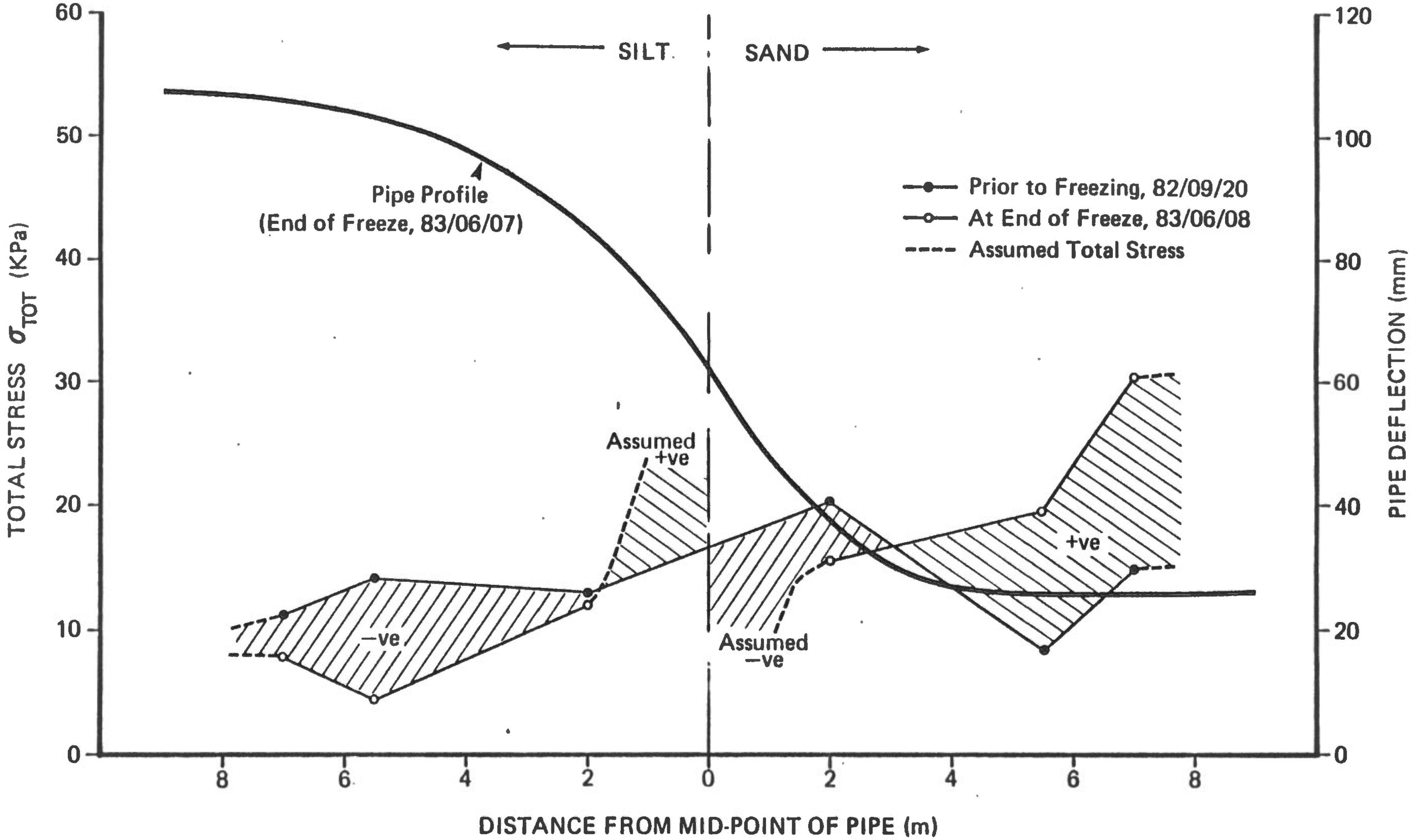

FIGURE 3.10 TOTAL STRESS IN SOIL BENEATH PIPE AT END OF FIRST FREEZE PERIOD (83/06/08)
(Pressure cells are located initially 46cm beneath pipe)

4. EXPERIMENTAL OBSERVATIONS - THAW PERIOD

4.1 General

Once the thaw period was initiated the soil surface became very soft and muddy, particularly at the silt end. Protective mats were laid down as walking paths to minimize surface disturbance. The surface thermocouples became badly disturbed and had to be temporarily removed. As the soil thawed and the previously frozen pore water became liberated, the water table tended to rise. To maintain the desired water level of 90cm below surface, water was pumped regularly from each of the 6 well points. At times as much as 240L of water per day were pumped. Records have been maintained of all water added or removed from the system during the course of the experiment.

4.2 Thermal Regime

As previously discussed the reliability of much of the thermal data collected during the thaw period has been reduced due to the problems with the data acquisition system. However, Figures 4.1 and 4.2 showing the changing temperature profiles beneath the pipe in the silt and sand respectively have been prepared using the limited number of thermisters available and by correcting for any anomalies with the thermocouple measurements. The graphs are probably accurate to $\pm$ 0.25°C. The recession of the 0° isotherm beneath the pipe during thaw is shown in Figure 4.3. This figure illustrates the more rapid degeneration of the frost bulb around the pipe in the sand than in the silt due to lower ice contents and the relatively higher thermal conductivity of the sand.

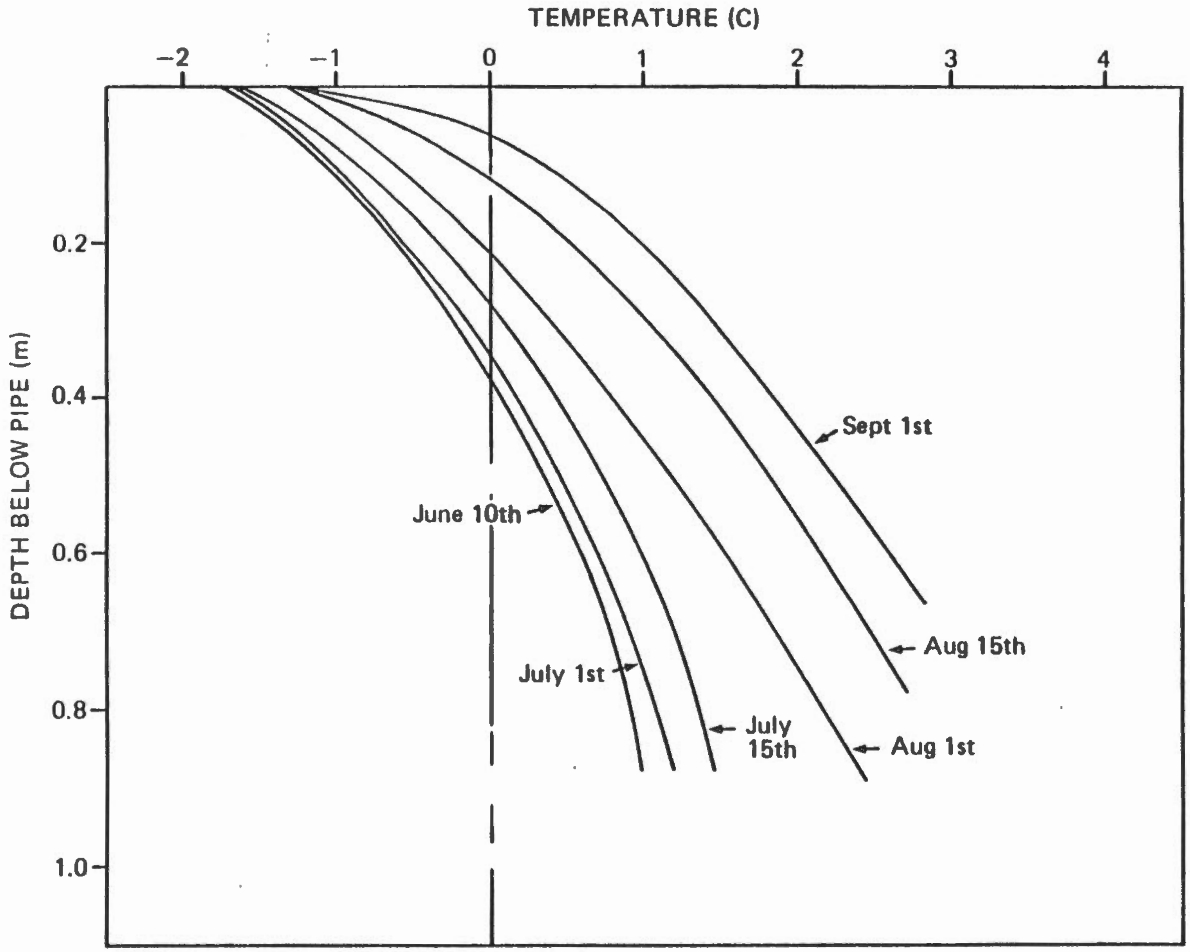

FIGURE 4.1 TEMPERATURE PROFILES BENEATH PIPE IN SILT (SECTION BB) DURING SURFACE THAW, 1983

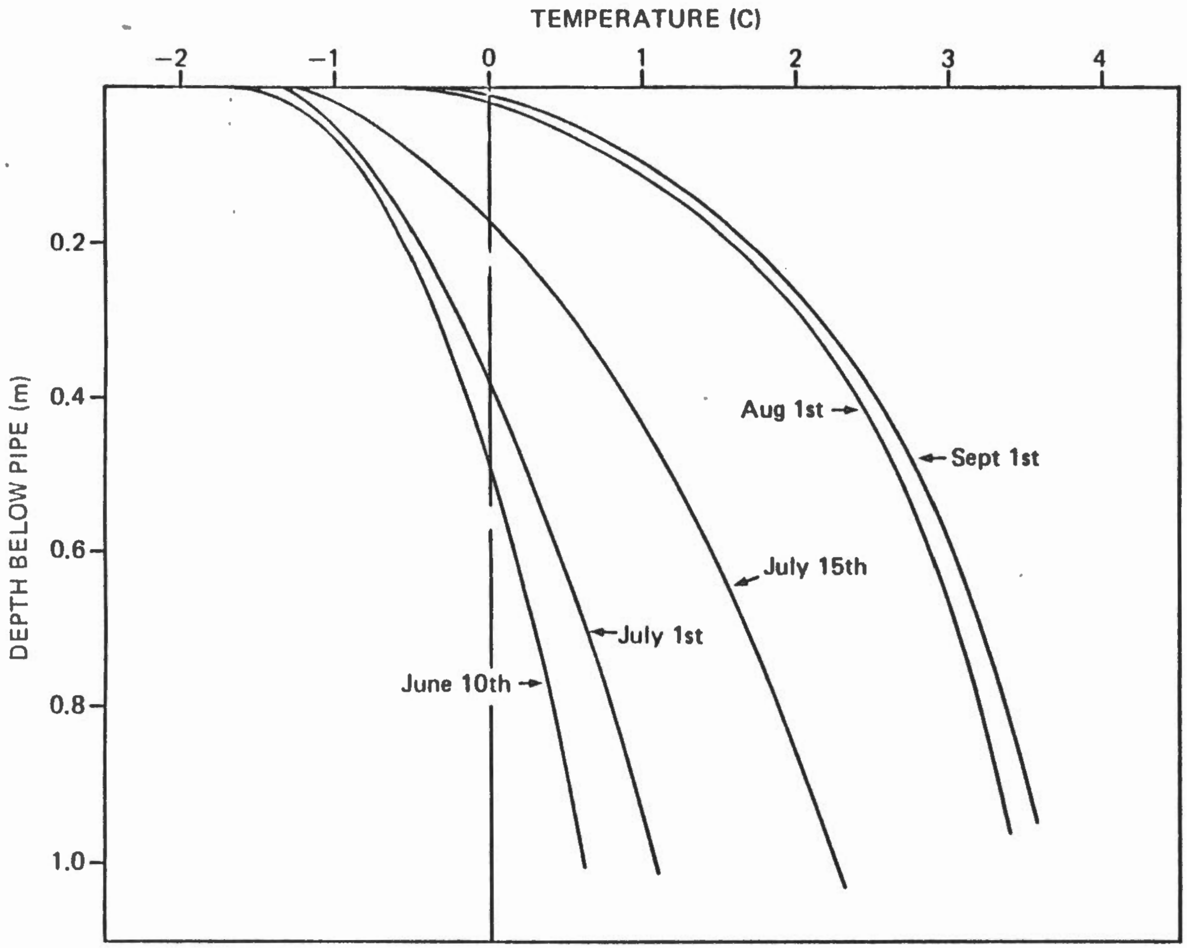

FIGURE 4.2 TEMPERATURE PROFILES BENEATH PIPE IN SAND (SECTION AA) DURING SURFACE THAW, 1983

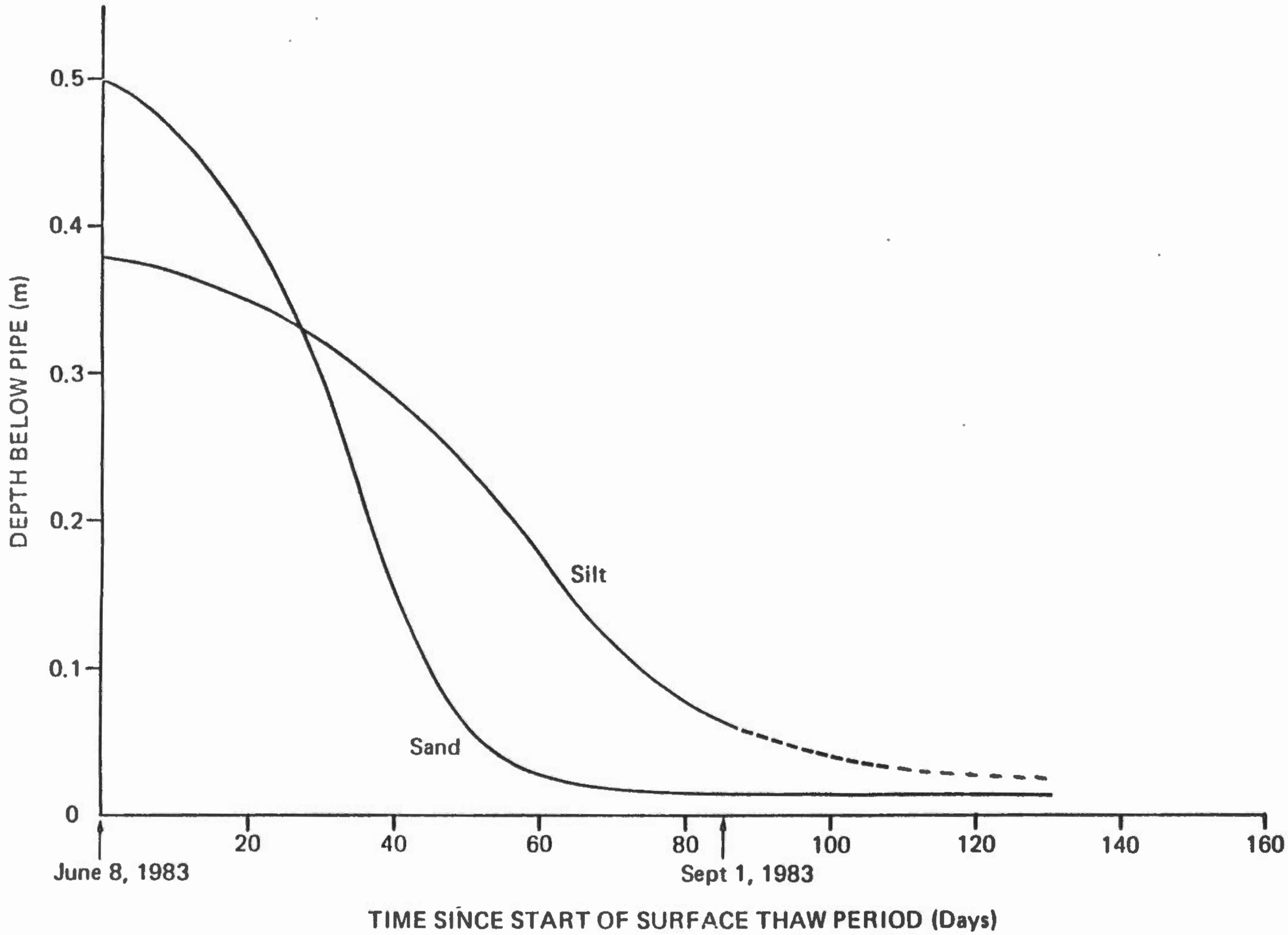

FIGURE 4.3 RECESSION OF FROST FRONT BENEATH PIPE DURING SURFACE THAW, 1983

4.3 Pipe Deformation

Figure 4.4 shows the evolution of the pipe profile during the thawing period of the experiment. In accordance with the temperature data of Figure 4.3 the initial rate of thaw settlement of the pipe is much more rapid in the sand than in the silt. The residual heave of the pipe at the end of the thaw period is approximately 10 to 20mm in the silt and 6 to 10mm in the sand.

Figure 4.5 shows the decrease in bending stress of the pipe during thaw as measured by a series of the strain gauge couples mounted on the exterior of the pipe. One point of interest is the reversal of the residual bending stress between 83-08-04 and 83-08-03. This concurs with the reversal of the sense of curvature of the pipe profile for 83-08-30 shown in Figure 4.4.

4.4 Soil Consolidation and Dilation

Figures 4.6 to 4.9 show the variation in surface contours during the thaw cycle. Figure 3.8 indicates that by the end of the freeze cycle, towards the sides of the laboratory where the pipe had no effect, the silt and the sand had heaved approximately 60 to 70mm and 20 to 30mm respectively. By the end of the thaw cycle, Figure 4.9 shows the silt has settled below its original level by roughly 0 to 10mm. This additional settlement of the silt can be attributed to (a) compaction of the surface due to the small amounts of pedestrian traffic during thawing; and (b) consolidation of the silt due to the increased effective stress caused by negative pore pressures within the frozen silt and beneath the frost front during freezing.

The sand on the other hand has maintained a residual "heave" of roughly 5 to 10mm. This indicates that the sand has remained in a dilated state following the thaw.

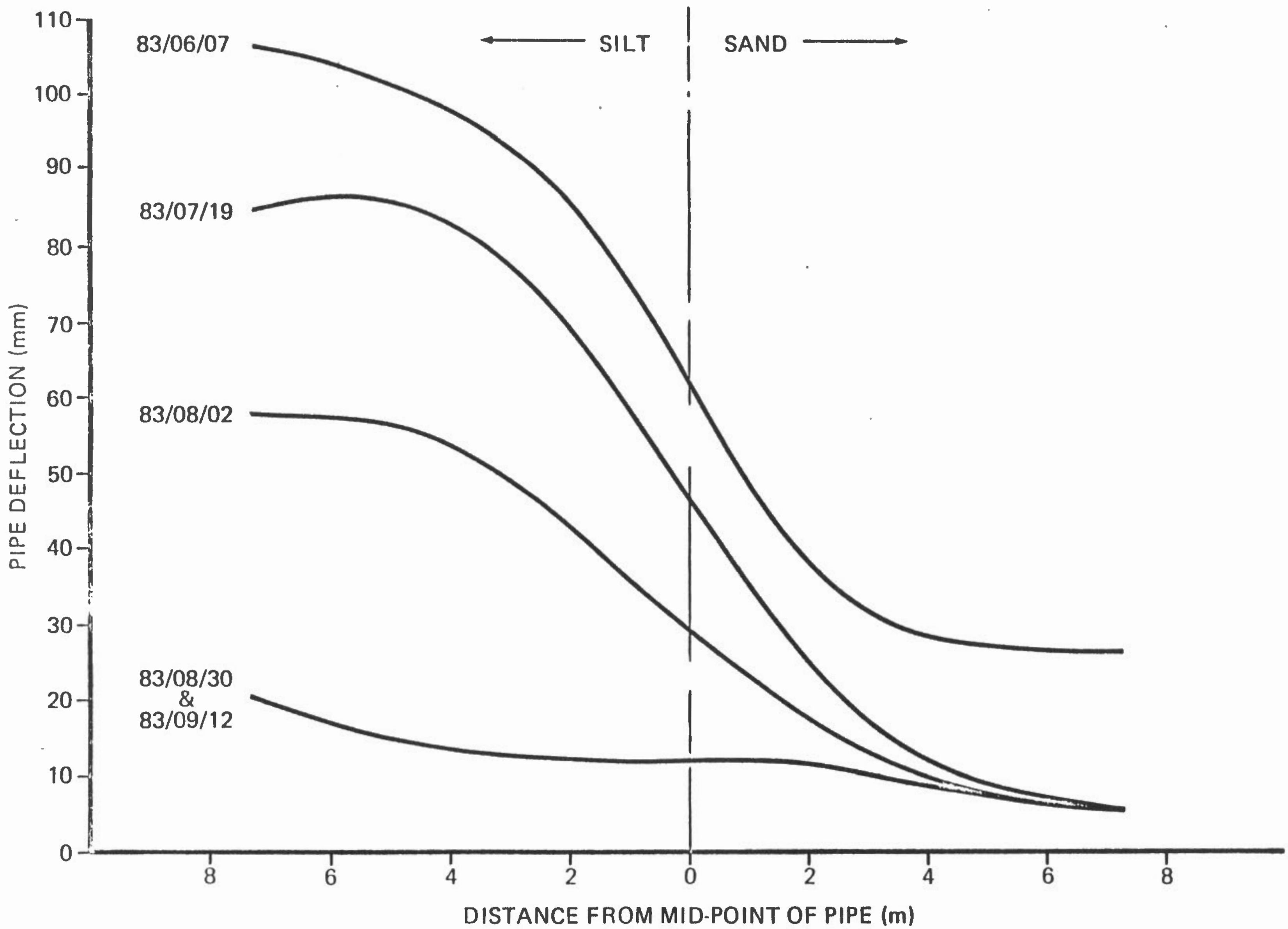

FIGURE 4.4 EVOLUTION OF PIPE PROFILE DURING SURFACE THAW

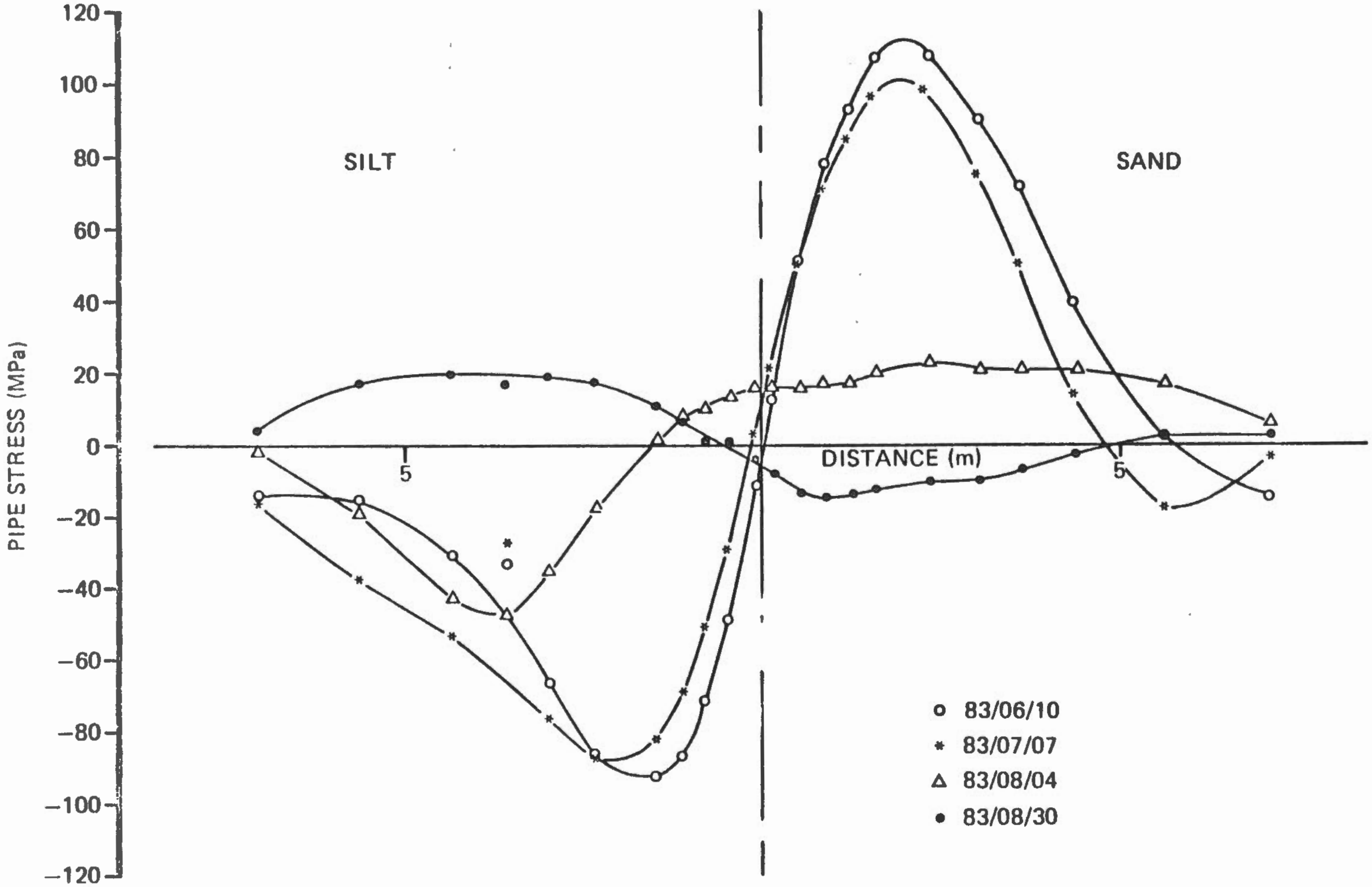

FIGURE 4.5 DISTRIBUTION OF BENDING STRESS IN PIPE DURING SURFACE THAW
(Computed from strain gauge readings)

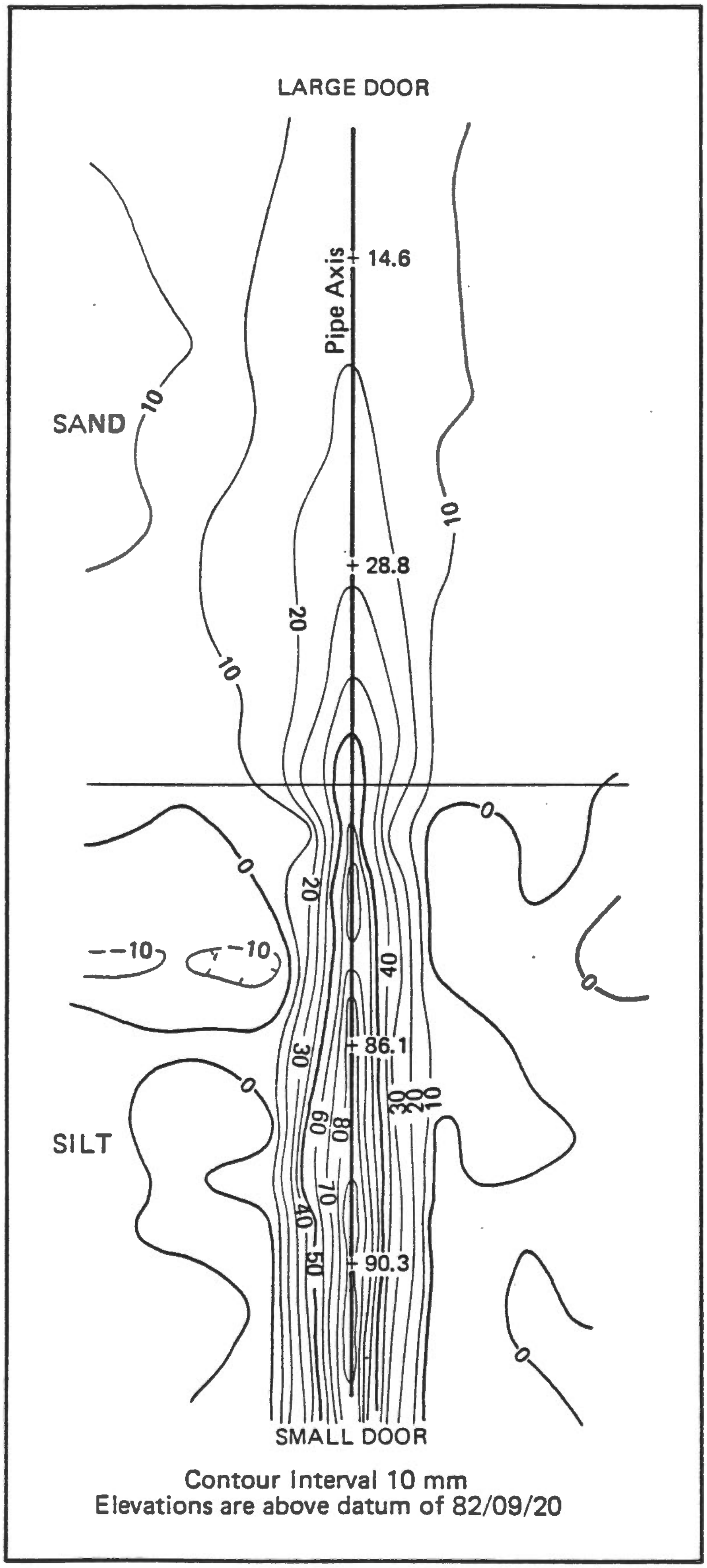

FIGURE 4.6 ELEVATION OF SOIL SURFACE
5 WEEKS AFTER START OF THAW 83/07/12

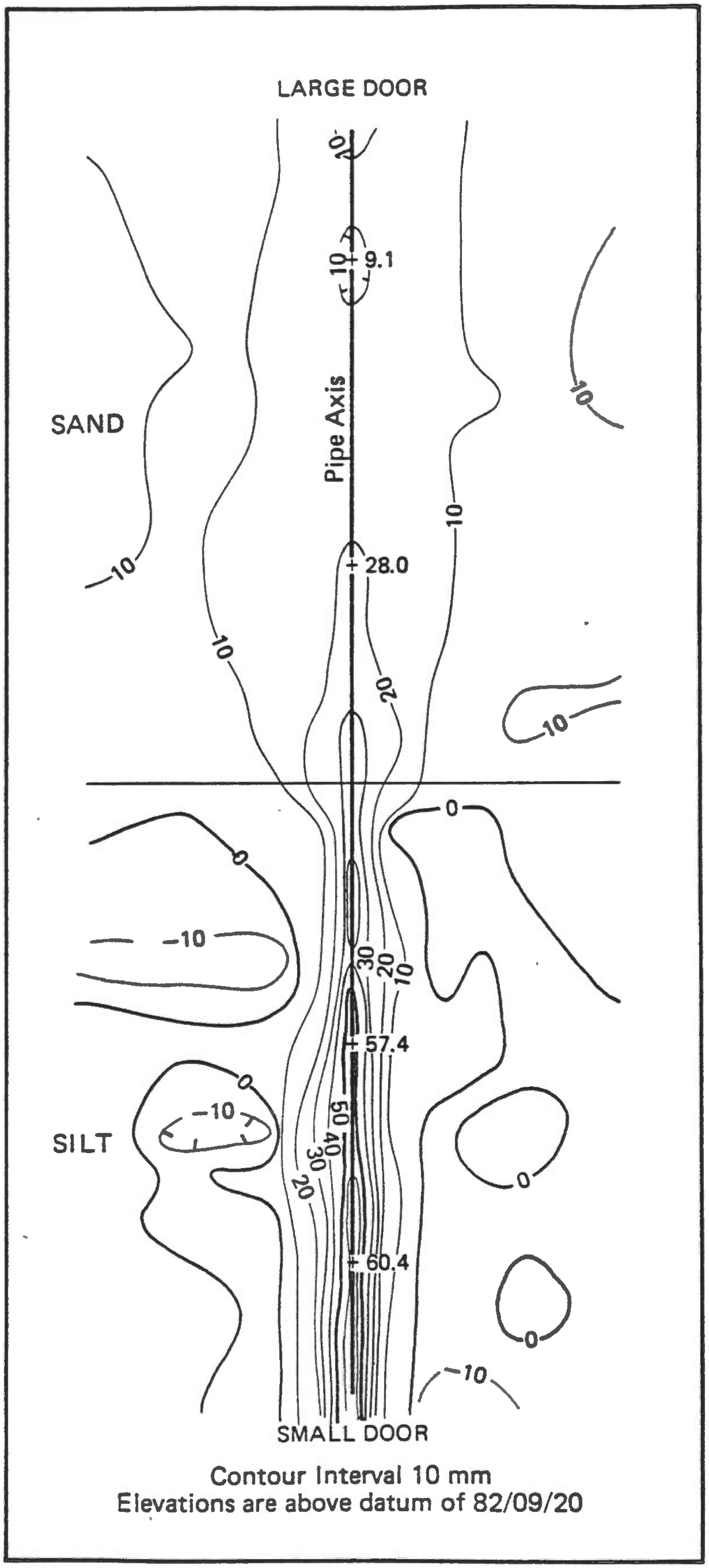

FIGURE 4.7 ELEVATION OF SOIL SURFACE 7 WEEKS AFTER START OF THAW 83/07/26

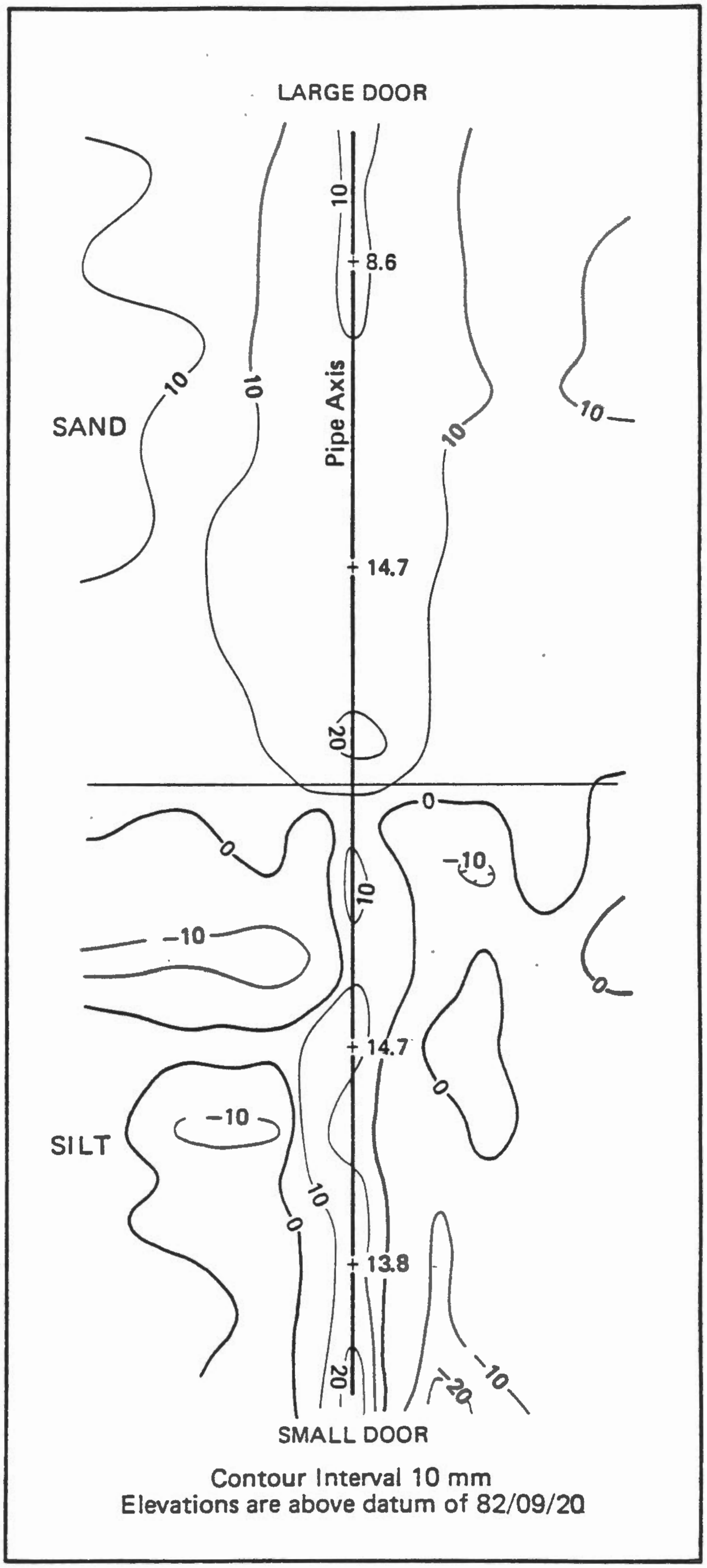

FIGURE 4.8 ELEVATION OF SOIL SURFACE 11 WEEKS AFTER START OF THAW 83/08/23

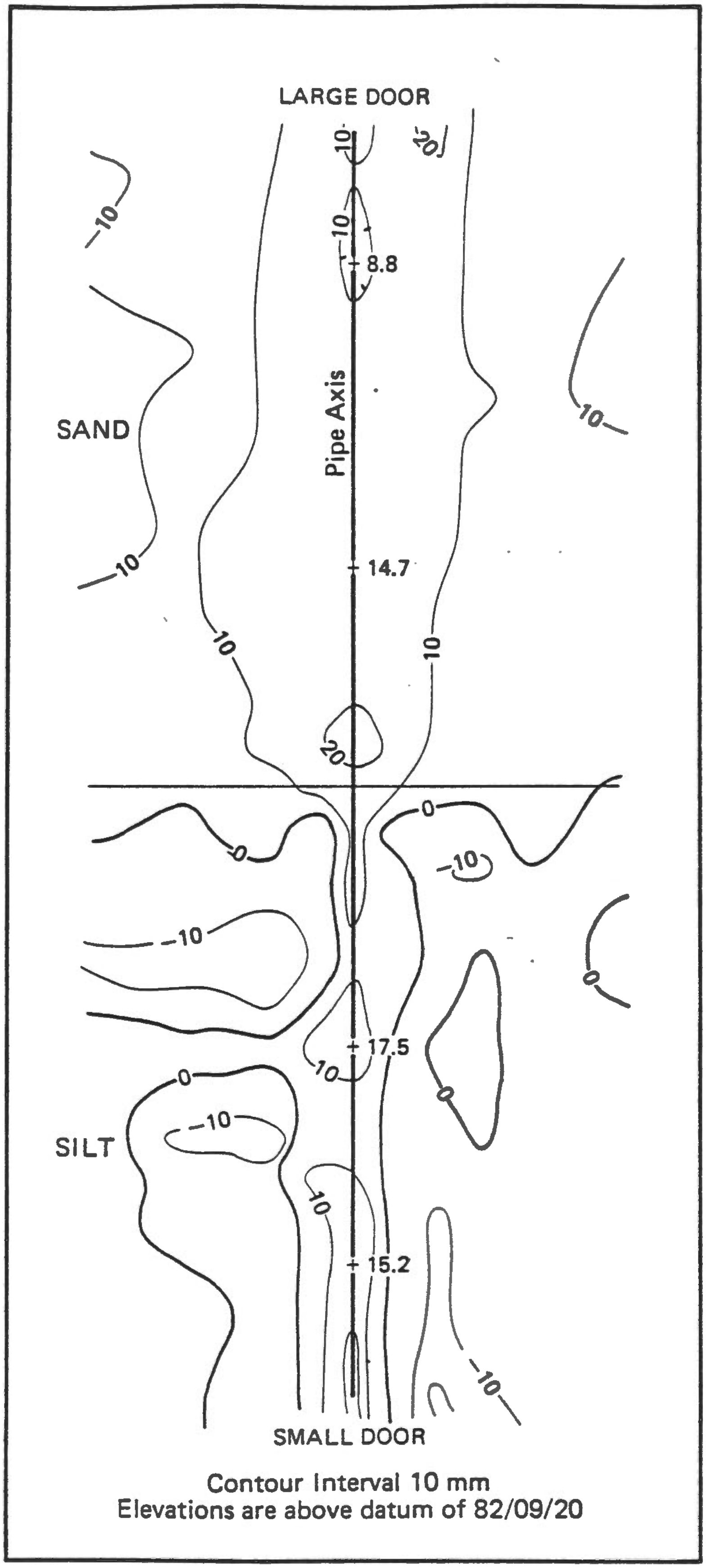

FIGURE 4.9 ELEVATION OF SOIL SURFACE 14 WEEKS AFTER START OF THAW 83/09/12

Periodic measurements of the density profile were made of the sand and silt during the experiment using the French designed "double-sonde" nuclear density machine. As yet not all of this data has been reduced and is therefore not presented here. It is hoped however, that this information will indicate the degree of consolidation and/or dilation and over what depths it has occurred.

4.5 Total Stress Induced in Soil

The evolution of the vertical component of total stress in the soil during the thaw period has been shown on Figures 4.10 and 4.11. The values for total stress have been determined from 6 Glotzl pressure cells situated originally 46cm beneath the pipe. The figures indicate a general decrease in total stress during the thaw period reflecting relaxation of the pipe. Similar to the figures of pipe stress a reversal of the change in total stress relative to the datum occurred between 83-07-15 and 83-08-31.

5. EXPERIMENTAL OBSERVATIONS - SECOND FREEZE PERIOD

5.1 General

The second freeze period began on October 17, 1983 and is expected to continue until sometime in the summer of 1984. Since this phase of the experiment is proceeding at the time of preparation of this report, results presented in this section are preliminary.

5.2 Thermal Regime

The modification made to the data collection system appear to have increased the accuracy of ground temperature measurements significantly.

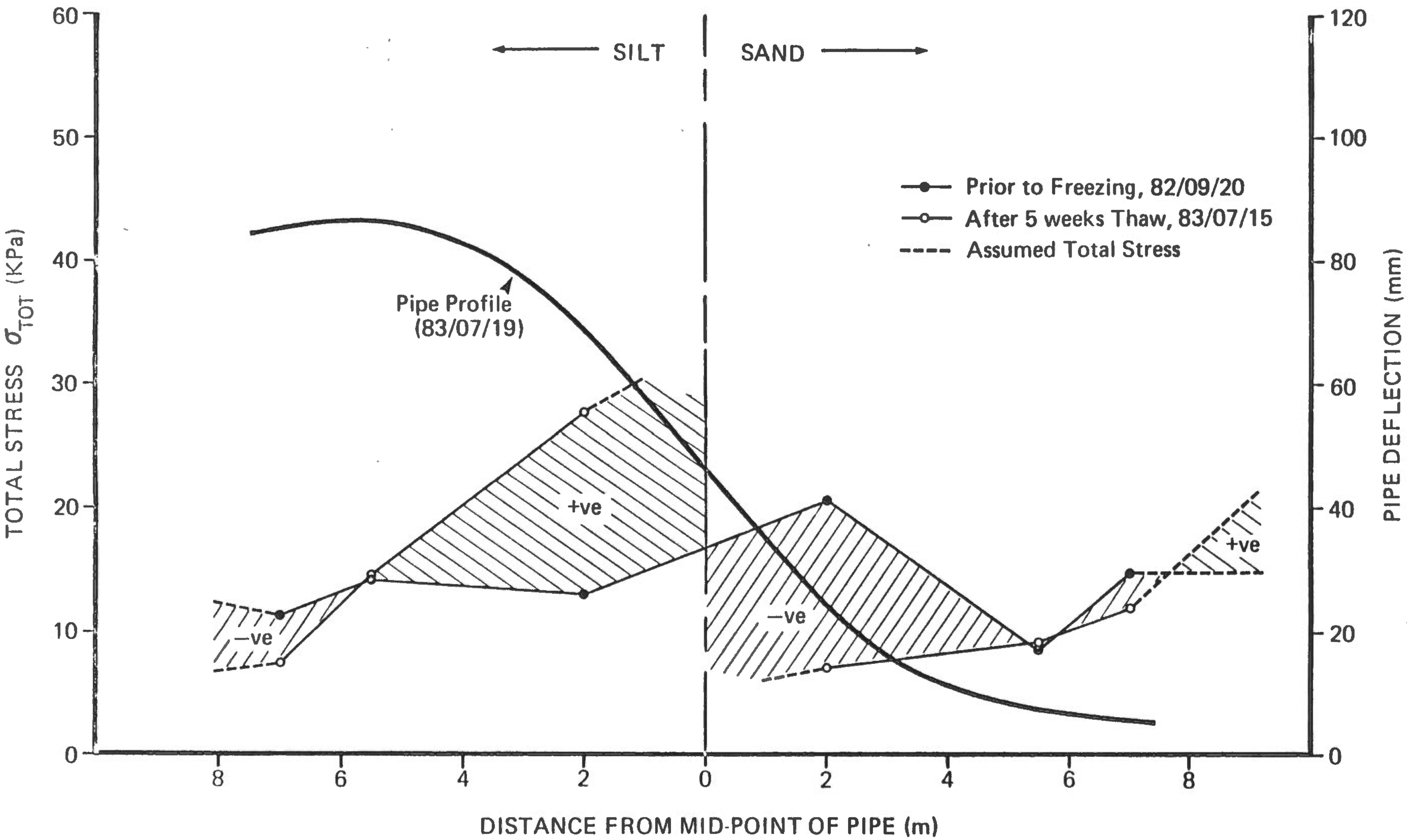

FIGURE 4.10 TOTAL STRESS IN SOIL BENEATH PIPE AFTER 5 WEEKS SURFACE THAW
(Pressure cells are located initially 46 cm beneath pipe)

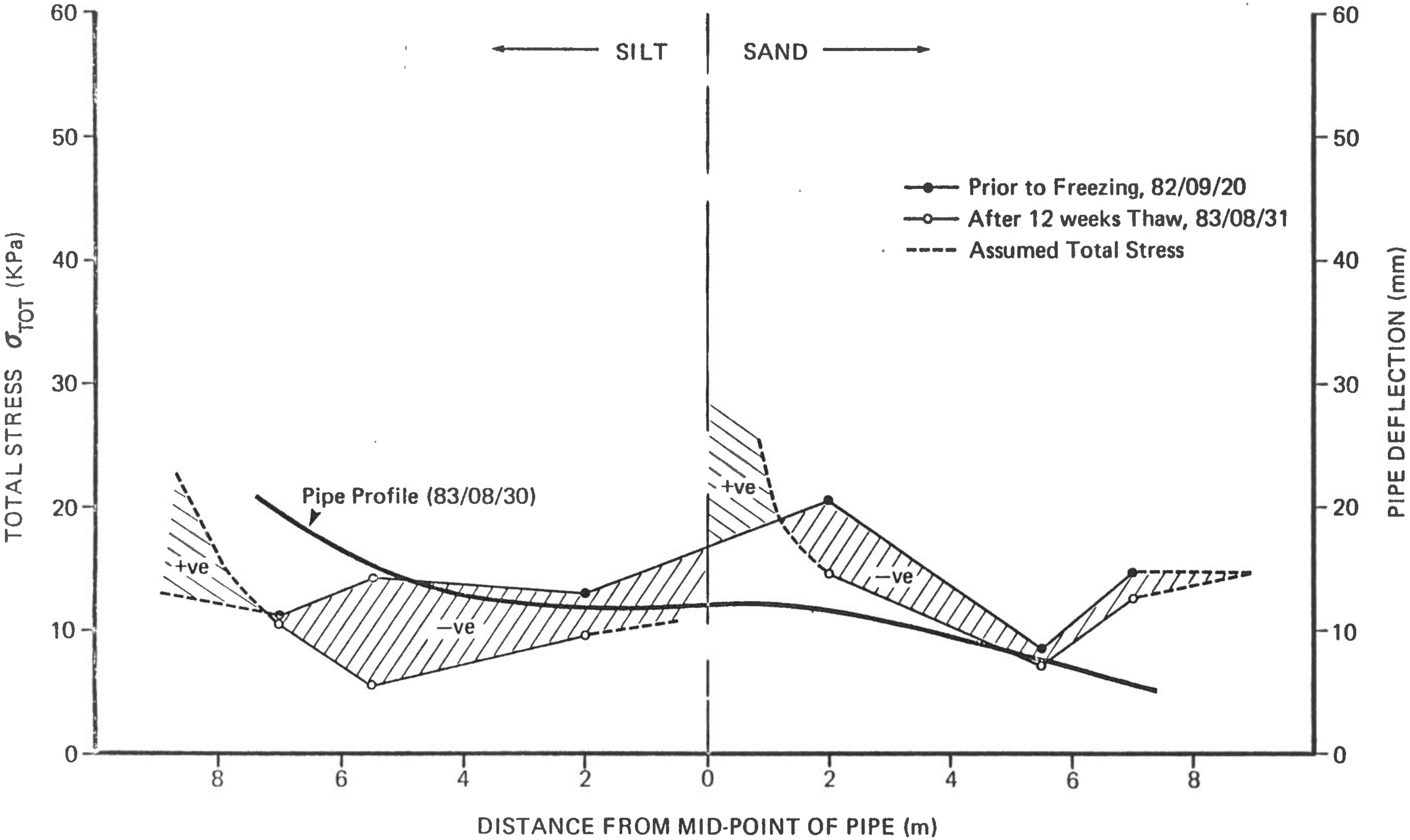

FIGURE 4.11 TOTAL STRESS IN SOIL BENEATH PIPE AFTER 12 WEEKS SURFACE THAW
(Pressure cells are located initially 46 cm beneath pipe)

The change of the temperature profiles beneath the pipe in the silt and the sand have been shown in Figures 5.1 and 5.2. The rate of progression of the $0^{\circ}C$ isotherm is shown on Figure 5.3. This reveals that the lower pipe temperature for the second freeze has significantly increased the rate of freeze compared to the first freeze period. In less than 60 days duration of the second freeze period, with pipe temperatures of $-5^{\circ}C$, the depth of frost penetration has exceeded that during the entire first freeze period of 250 days.

5.3 Pipe Deformation

Displacement and deformation of the pipeline is occurring in a similar manner to the first freeze period. However, the rate of heaving and build up of pipe stress is greater. Figure 5.4 shows the change of the profile of the pipe and Figure 5.5 shows the build up of pipe stress since the commencement of the second freeze period.

5.4 Surface Heave of Soils

The relative movement of the surface of the two soils during the first months of the second freeze period has been shown on Figures 5.6 and 5.7. These figures are contour maps indicating the net heave since the commencement of the second freeze period.

5.5 Total Stress Induced in Soil

The evolution of the vertical component of the total stress in the soil during the first months of the second freeze period is shown on Figures 5.8 and 5.9. This data was collected from 6 Glotzl pressure cells buried in the two soils at initial depths of 46cm beneath the pipe.

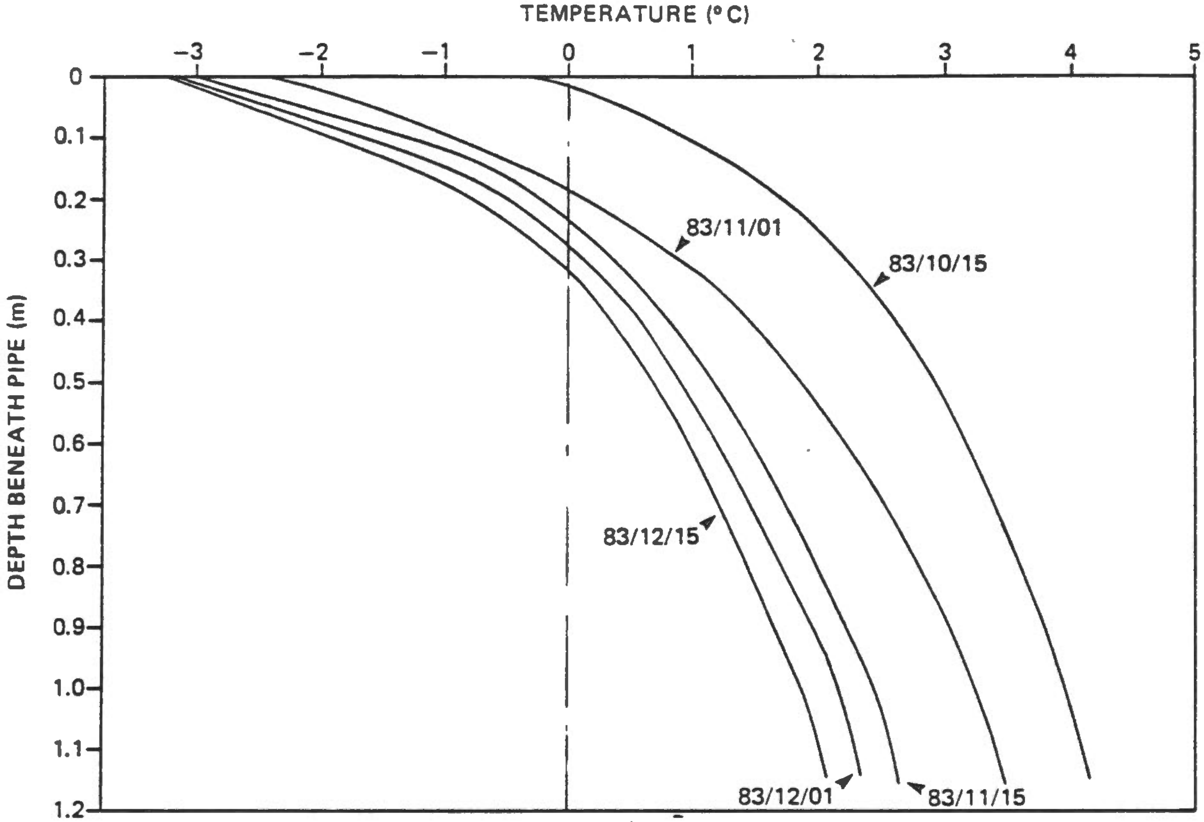

FIGURE 5.1 TEMPERATURE PROFILES BENEATH PIPE IN SILT (SECTION BB) DURING SECOND FREEZE PERIOD

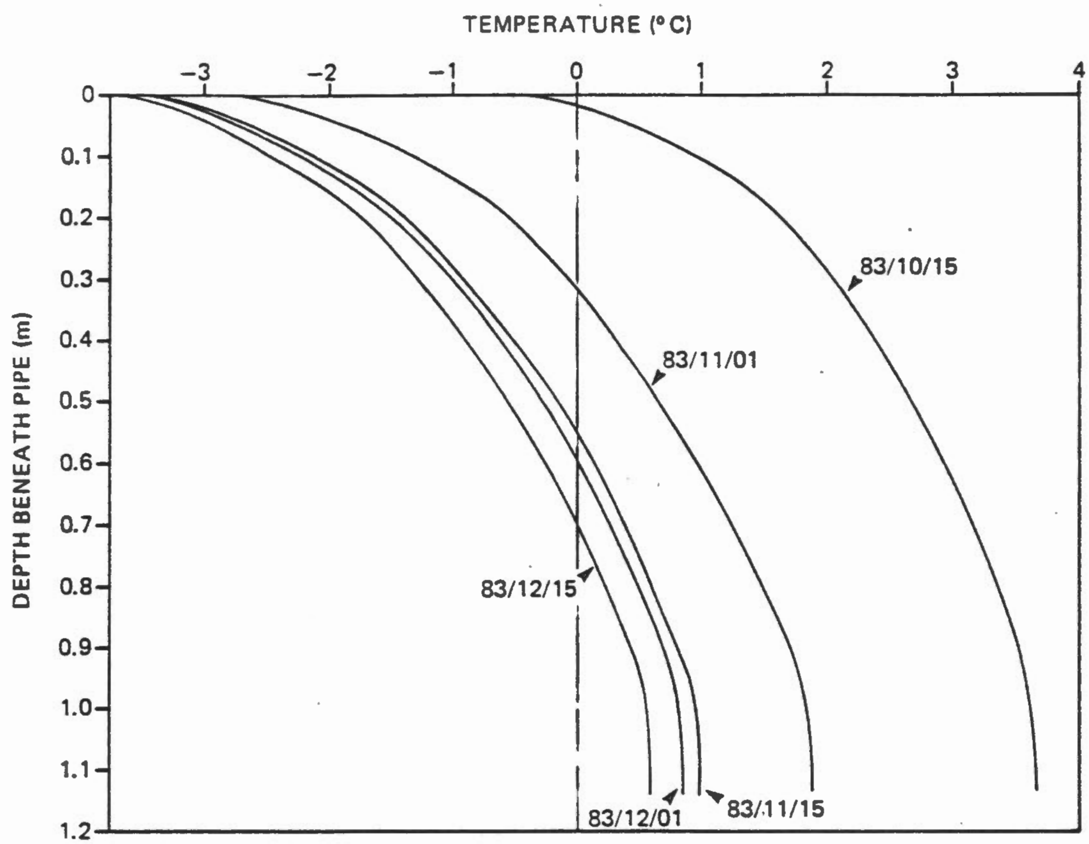

FIGURE 5.2 TEMPERATURE PROFILES BENEATH PIPE IN SAND (SECTION AA) DURING SECOND FREEZE PERIOD

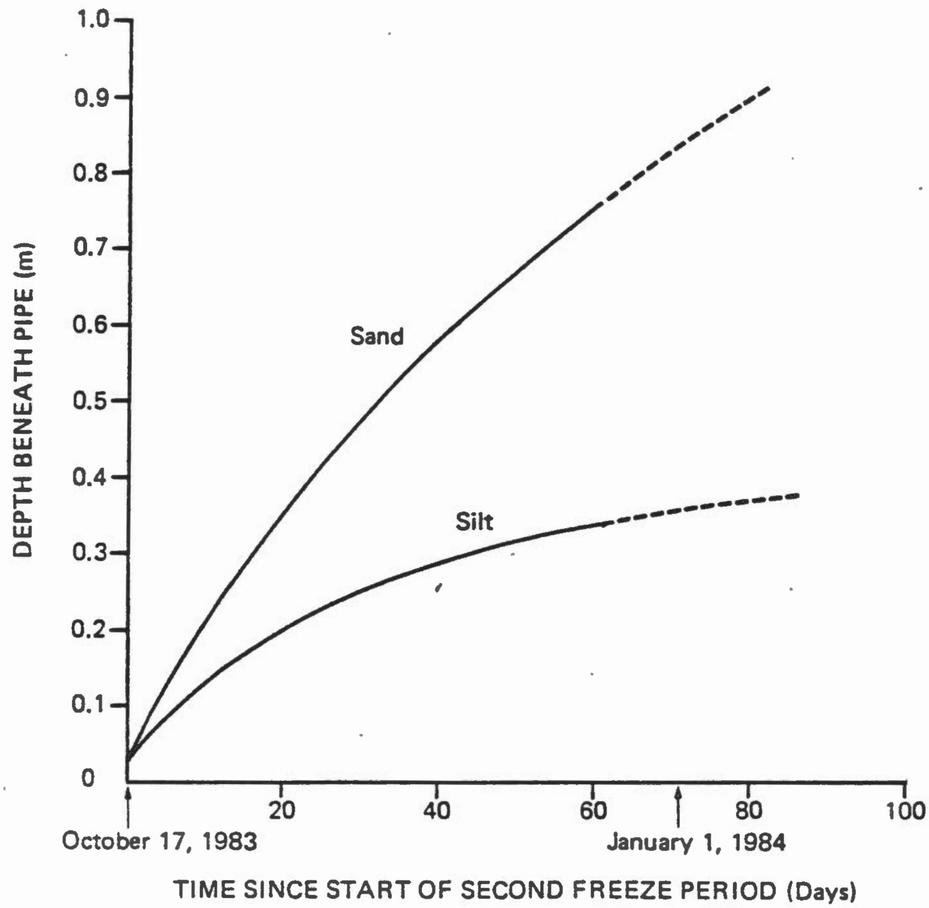

FIGURE 5.3 PROGRESSION OF FROST FRONT BENEATH PIPE DURING SECOND FREEZE PERIOD

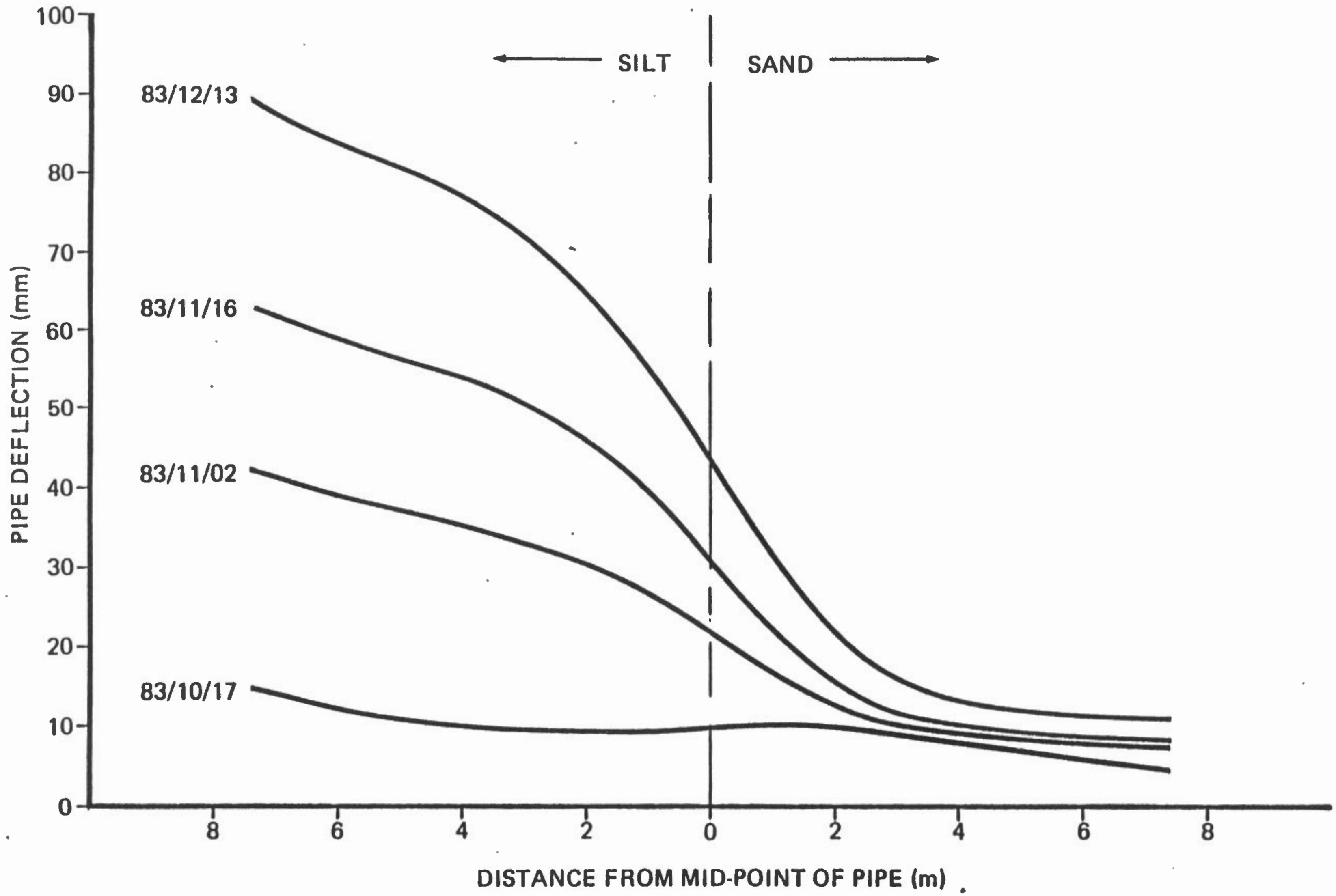

FIGURE 5.4 EVOLUTION OF PIPE PROFILE DURING SECOND FREEZE PERIOD

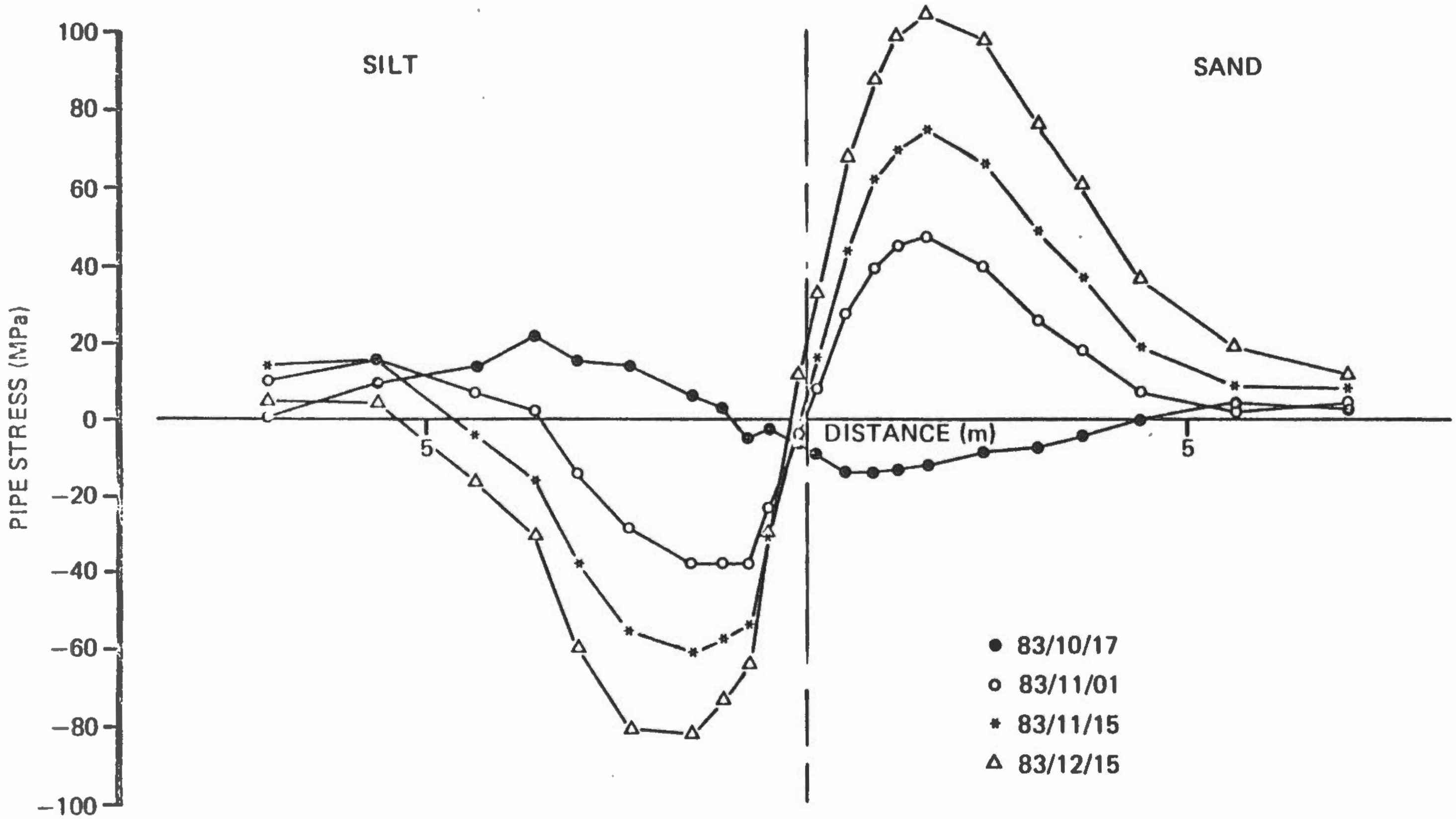

FIGURE 5.5 DISTRIBUTION OF BENDING STRESS IN PIPE DURING SECOND FREEZE PERIOD
(Computed from strain gauge readings)

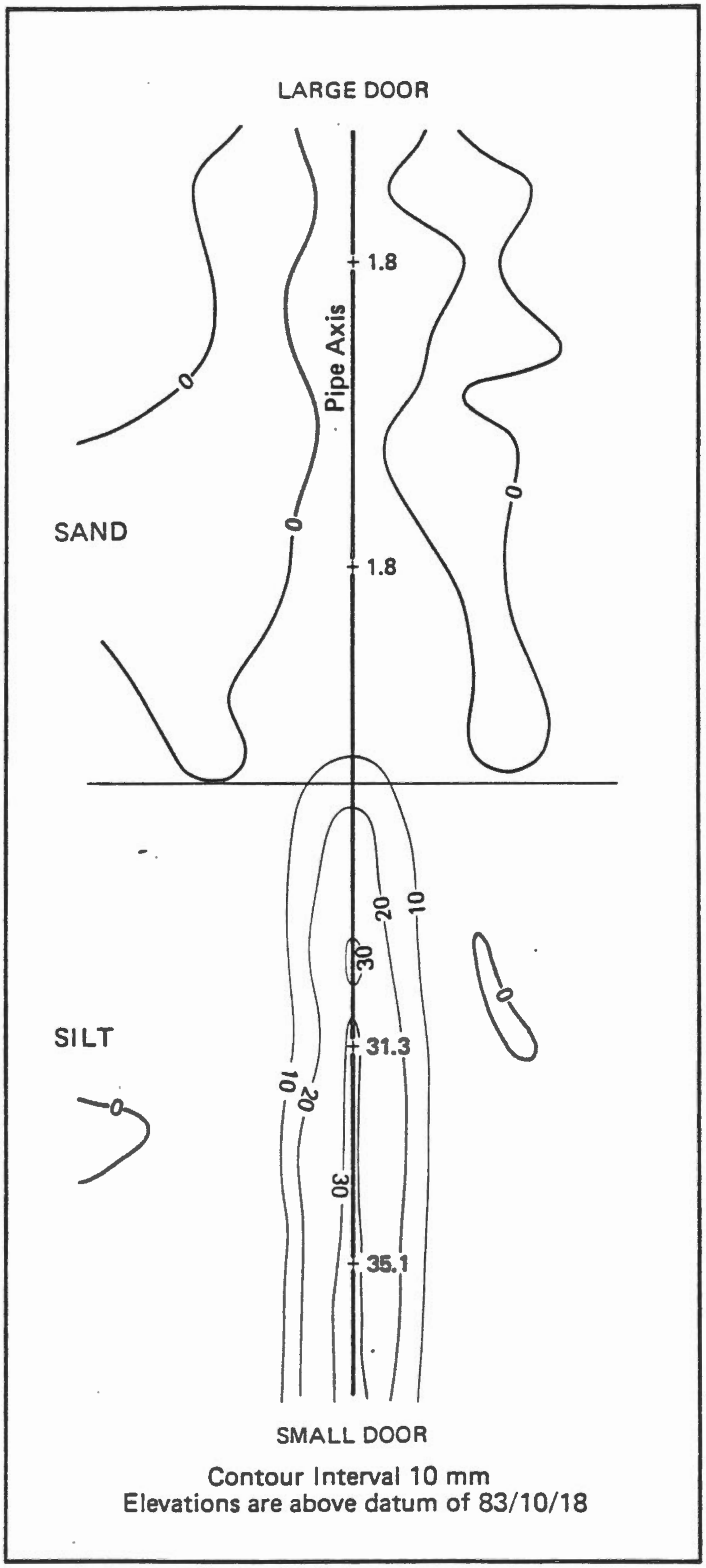

FIGURE 5.6 ELEVATION OF SOIL SURFACE 2 WEEKS AFTER START OF FREEZE 83/11/02

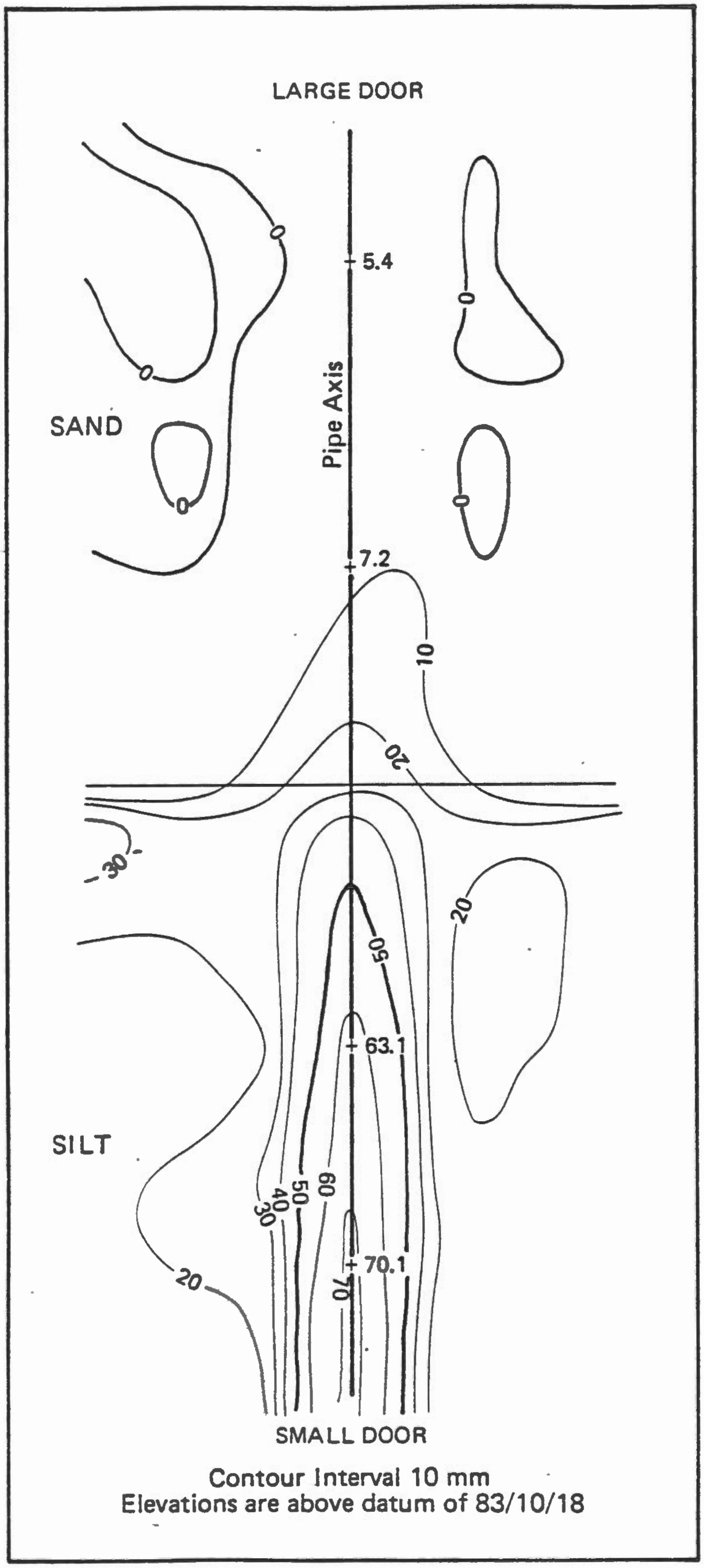

FIGURE 5:7 ELEVATION OF SOIL SURFACE 6 WEEKS AFTER START OF FREEZE 83/12/02

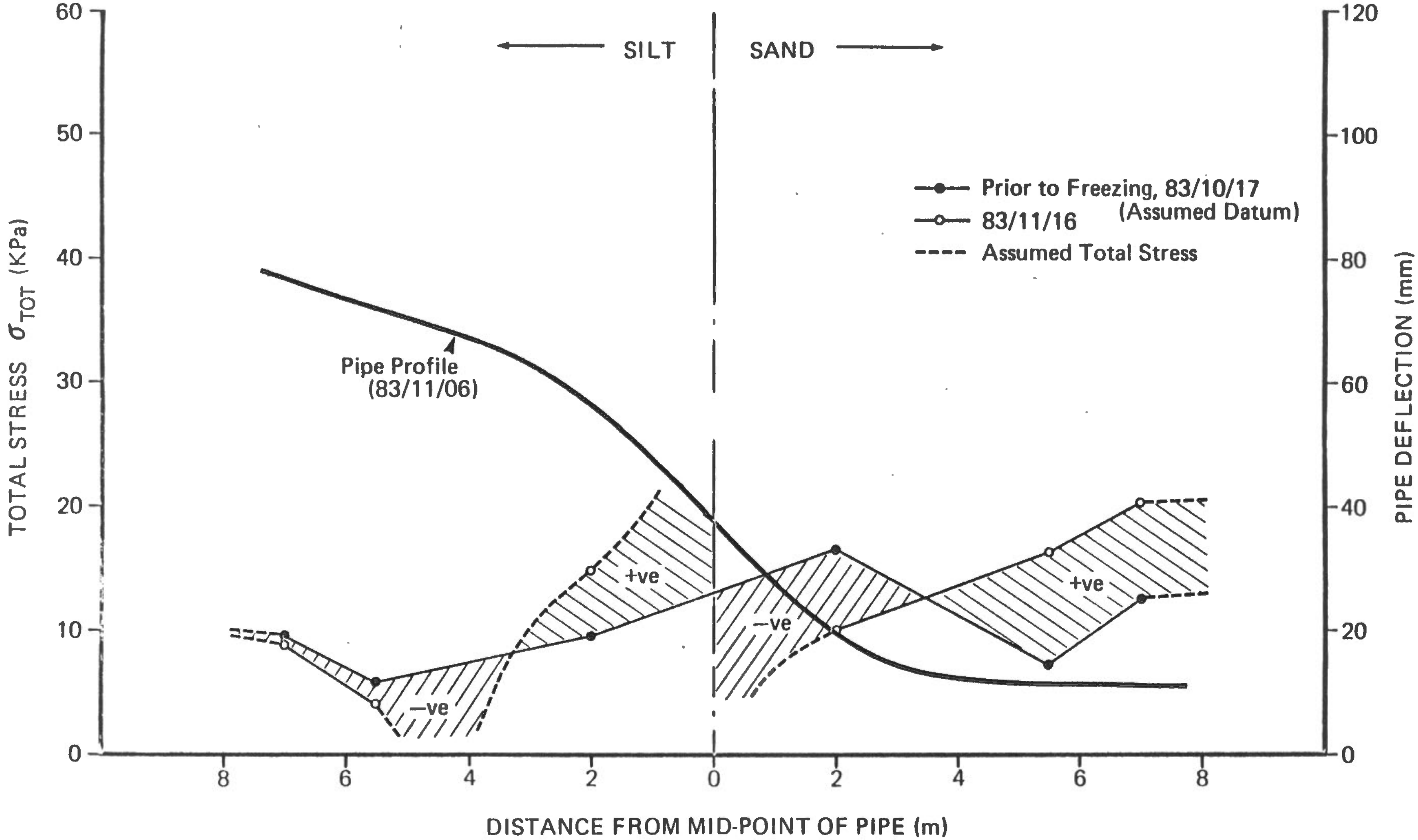

FIGURE 5.8 TOTAL STRESS IN SOIL BENEATH PIPE 4 WEEKS AFTER START OF SECOND FREEZE PERIOD (Pressure cells are located initially 46 cm beneath pipe)

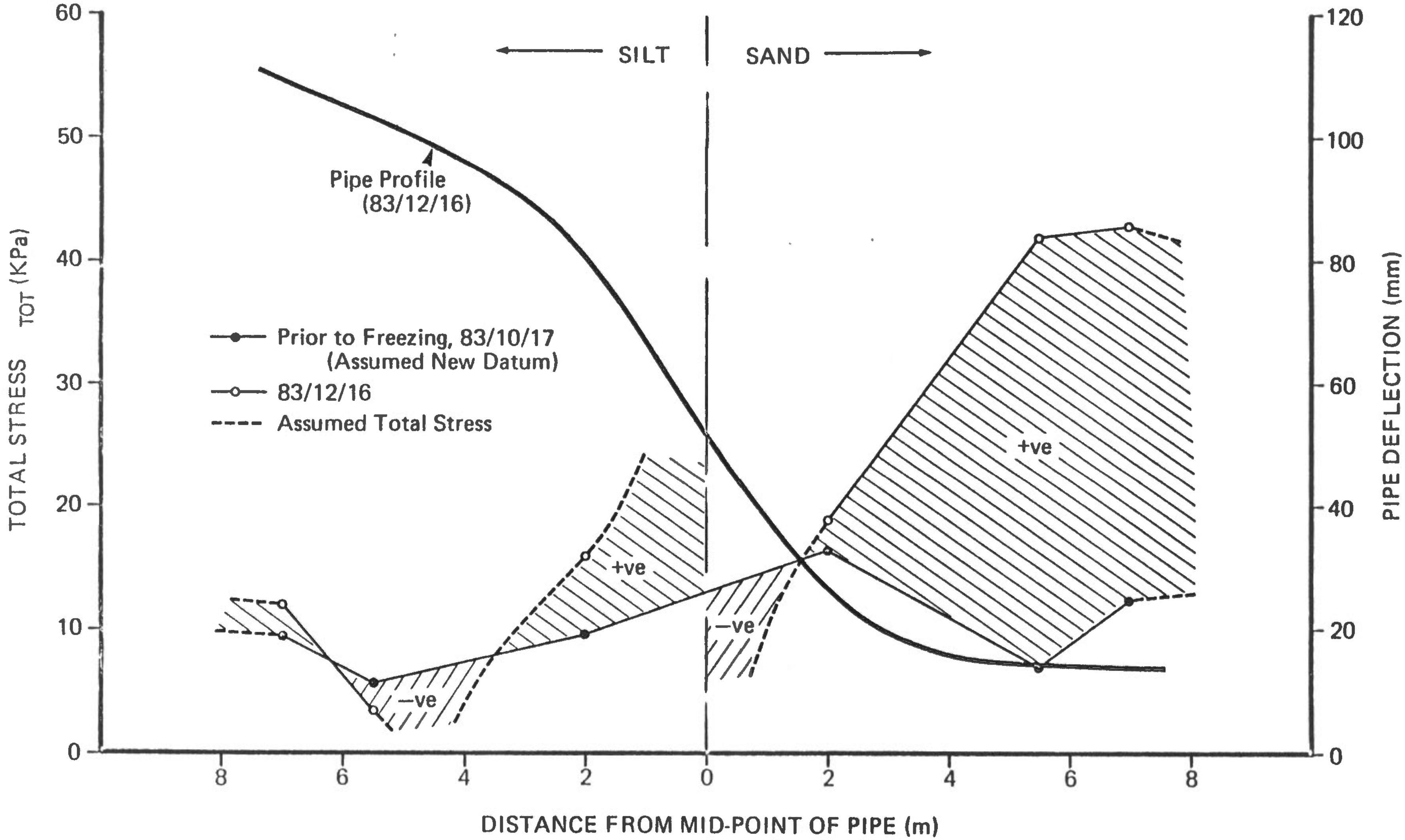

FIGURE 5.9 TOTAL STRESS IN SOIL BENEATH PIPE 8 WEEKS AFTER START OF SECOND FREEZE PERIOD (Pressure cells are located initially 46 cm beneath pipe)

A similar trend to that during the first freeze period can be observed. Adjacent to the sand-silt interface a positive heaving pressure occurs in the silt and a negative pressure occurs in the sand. The maximum values of the earth pressure in this zone appear to occur very close to the sand-silt interface. A zone of increase and decrease in total stress (relative to assumed datum at start of freeze) occur at the sand and silt ends respectively.

6. LABORATORY TESTING

6.1 General

Substantial laboratory testing has been carried out during the contract period, on the two soils used in the experiment. The testing has been undertaken in the Geotechnical Science Laboratories at Carleton University, and the laboratories of the Centre d'Ingenierie Nordique at Ecole Polytechnique. Laboratory testing is continuing, particularly on the strength properties of the frozen soils.

6.2 Frost Heave

A total of eleven frost heave tests have been performed to determine the heave characteristics of remolded samples of Caen silt. The tests were conducted with a modified 10cm diameter piston type frost heave cell, provided by Dr. B. Ladanyi of Ecole Polytechnique.

Two types of sample preparation were utilized in the testing. Seven tests were performed on samples prepared with a dynamic, proctor type compaction method. Four tests were performed on samples consolidated from a 50% water content soil slurry. Sample densities of about 1.75×10^3 kg/m^3

were used for all tests. After preparation, saturation and cooling of the test samples, a cold side base temperature of about $-5^{\circ}C$ was applied with a warm side temperature of about $1.5^{\circ}C$. The progress of the frost line was monitored with thermocouples embedded in the cell wall. Heave displacement was measured with a 0.005mm dial gauge and intake of water at the warm end of the cell was measured with a burrette.

Representative plots of heave vs. time for compacted and consolidated samples are shown as Figures 6.1 and 6.2. The test data and its usefulness in predicting frost heave during the freeze periods of the experiment will be further examined in a Master's thesis currently in preparation at Carleton University.

6.3 Suction-Water Content

The soil suction moisture content relationship for the Caen silt and the sand have been determined for the range of 0 to 6,000 kPa. A variety of apparatus including suction plates, pressure plates and pressure membrane apparatus were used. The procedure utilized for the testing is outlined in Geotechnical Science Laboratories Report LTR-11 (1979).

The relation of applied suction pressure to water content for the two soils is presented as Figure 6.3. This shows that significant amounts of water, particularly in the silt, are present in the soils even with very high suction pressure. The relationship of suction to water content has been shown to be related to the unfrozen water content relationship of frozen soils (Williams, 1983). This is because the main cause of freezing point depression is the suction (free energy) developed in the water as the water content of a soil is reduced. An approximate conversion of suction to temperature has been carried out on the data obtained from the suction

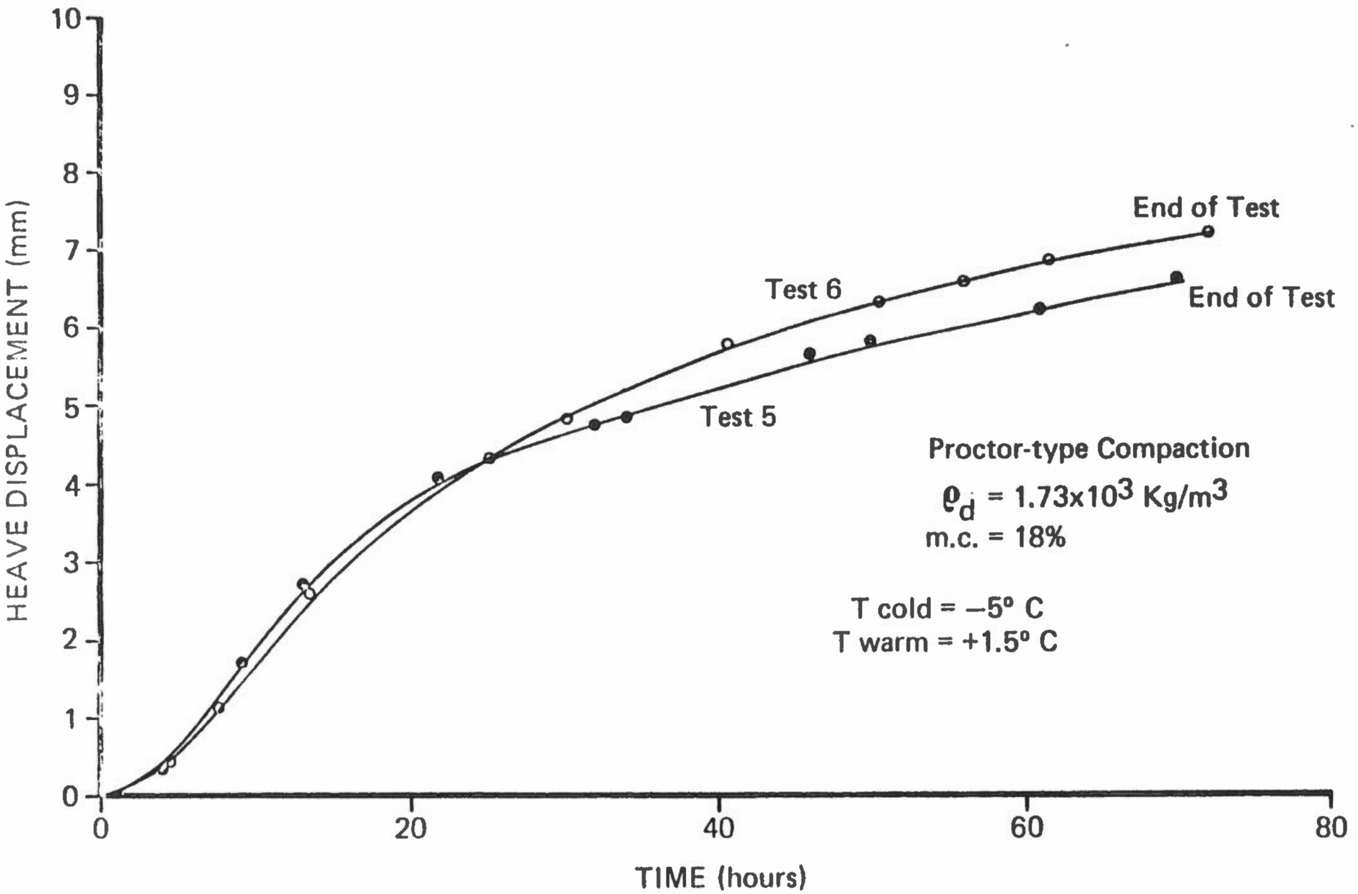

FIGURE 6.1 FROST HEAVE VS. TIME FOR CAEN SILT COMPACTED IN LAYERS

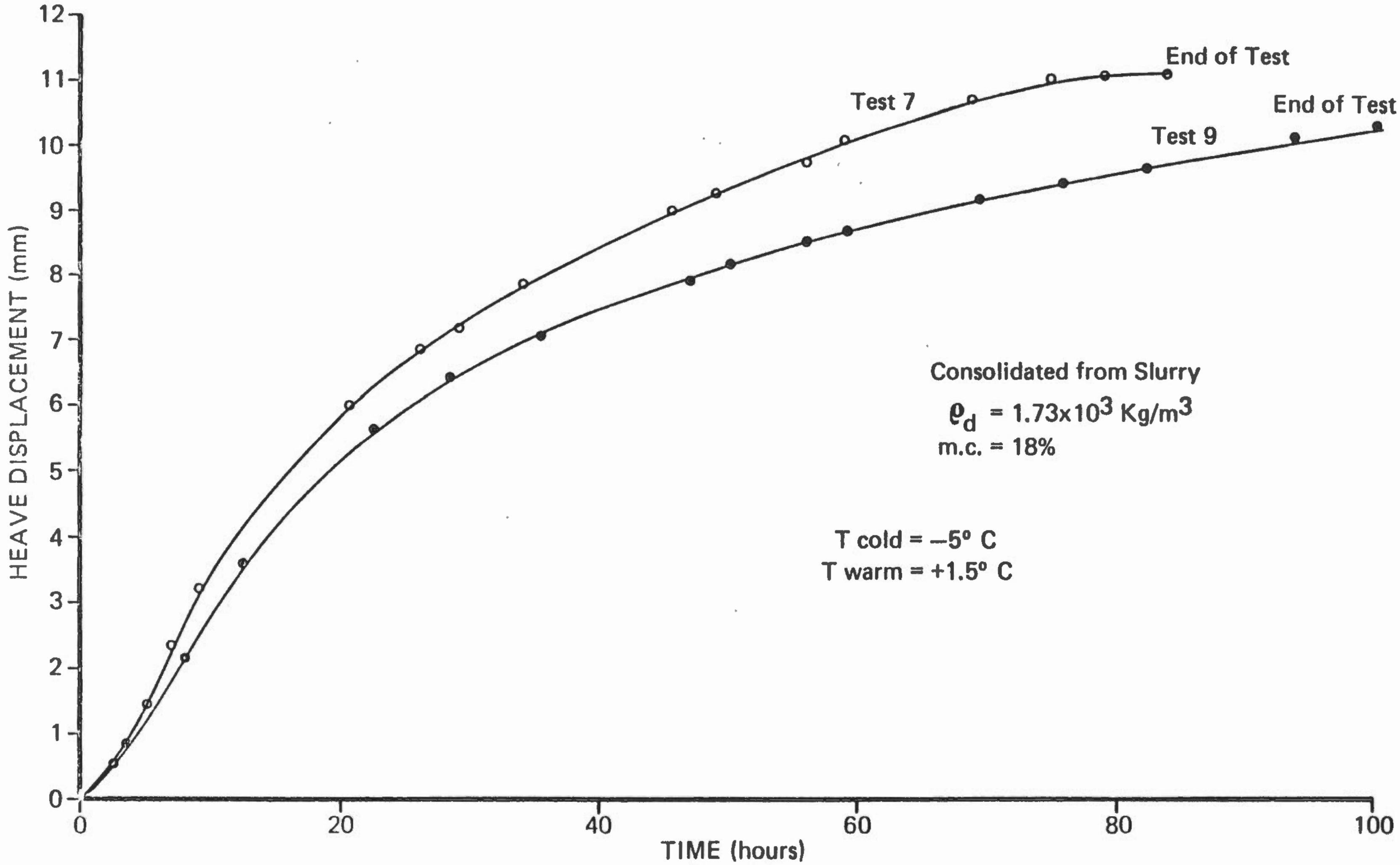

FIGURE 6.2 FROST HEAVE VS. TIME FOR CAEN SILT CONSOLIDATED FROM A SLURRY

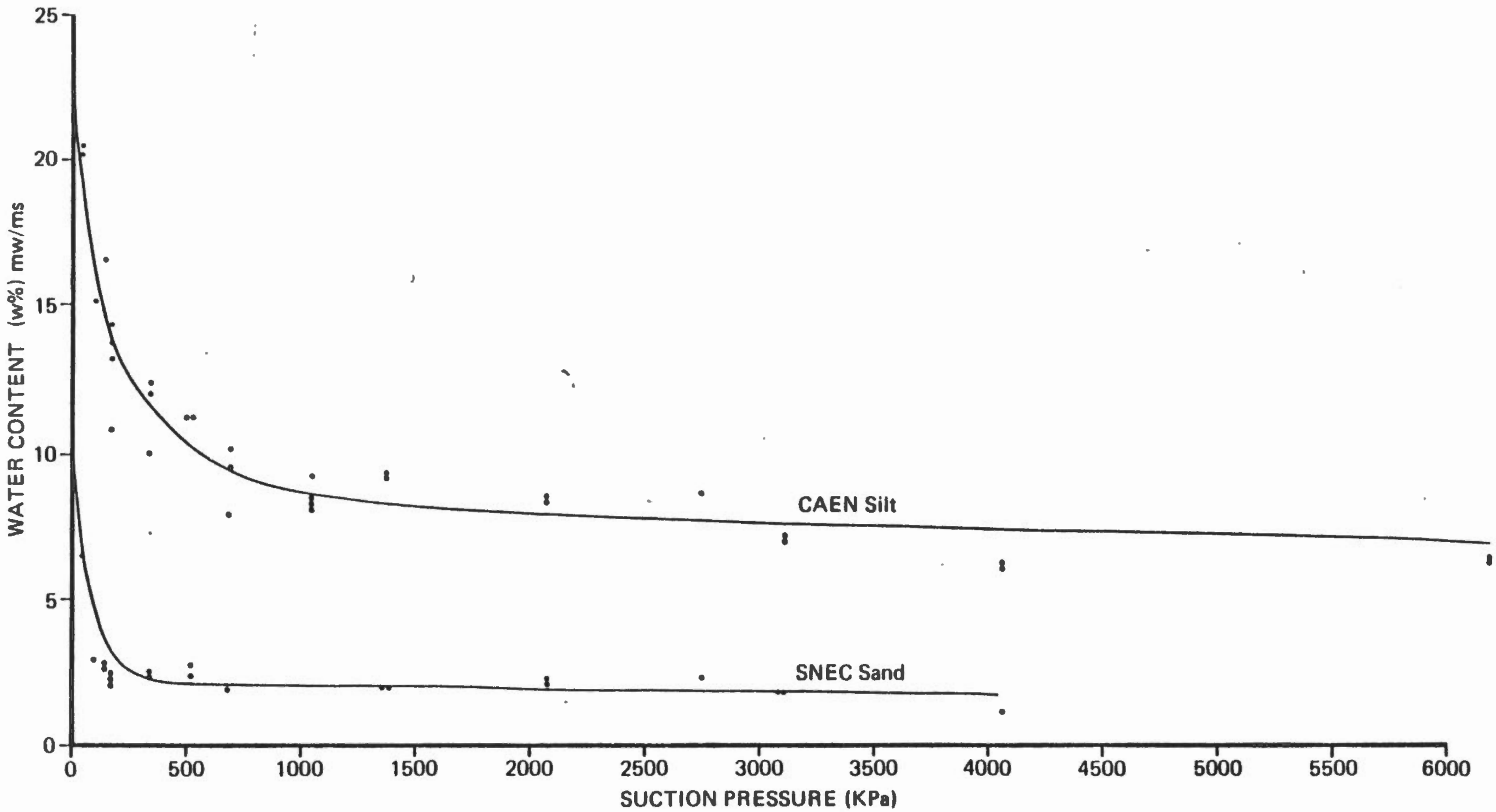

FIGURE 6.3 SUCTION-MOISTURE CONTENT CURVES FOR CAEN SILT AND SNEC SAND

testing according to the method described in Geotechnical Science Laboratories Report LTR-111 (1979). This information has been presented as Figure 6.4.

6.4 Mechanical Properties

The behaviour of frozen soils under loading has been shown to be very complex and dependent on a number of variables. Testing has been carried out in the cold rooms of the Centre d'Ingeniere Nordique to determine the mechanical properties of the frozen sand and silt. To date, a number of tests have been performed with the Menard pressure meter and an additional test program is underway with a triaxial apparatus.

The results from the pressure meter testing, including a description of the experimental method have been described in a Master's thesis recently completed at Ecole Polytechnique (Lemaire, 1983). The tests were carried out in a specially designed test cell 47cm in diameter and 45.5cm in height, with a central reservoir 7.4cm in diameter. A Menard type GC pressure meter with a maximum pressure capacity of 10 MPa was placed in the central cavity. Test samples were carefully prepared, cooled for three days at $-10^{\circ}C$ and then raised to the desired test temperature of $-1.5^{\circ}C$. Constant load creep for tests were performed on the samples to determine the effect of time on the behaviour of the soils.

The results from the pressure meter testing are presented for various uniaxial stresses on strain-time curves shown as Figure 6.5.

7. CONCLUSIONS

Work carried out during the contract year can be summarized as follows:

(1) The development of frost heave, the deformation of the pipe and the

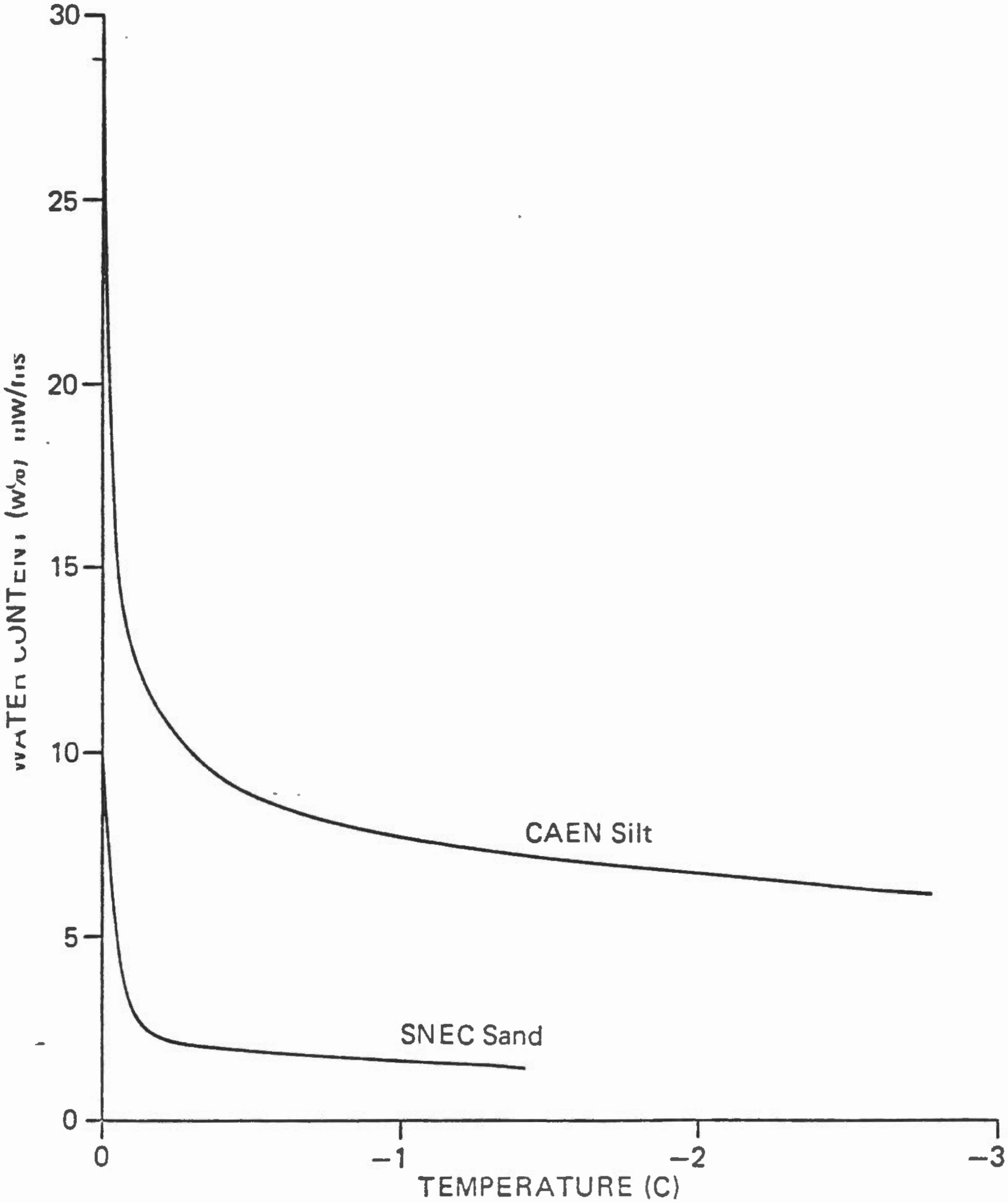

FIGURE 6.4 UNFROZEN WATER CONTENT VS. TEMPERATURE FOR CAEN SILT AND SNEC SAND
(From suction-moisture content relationship)

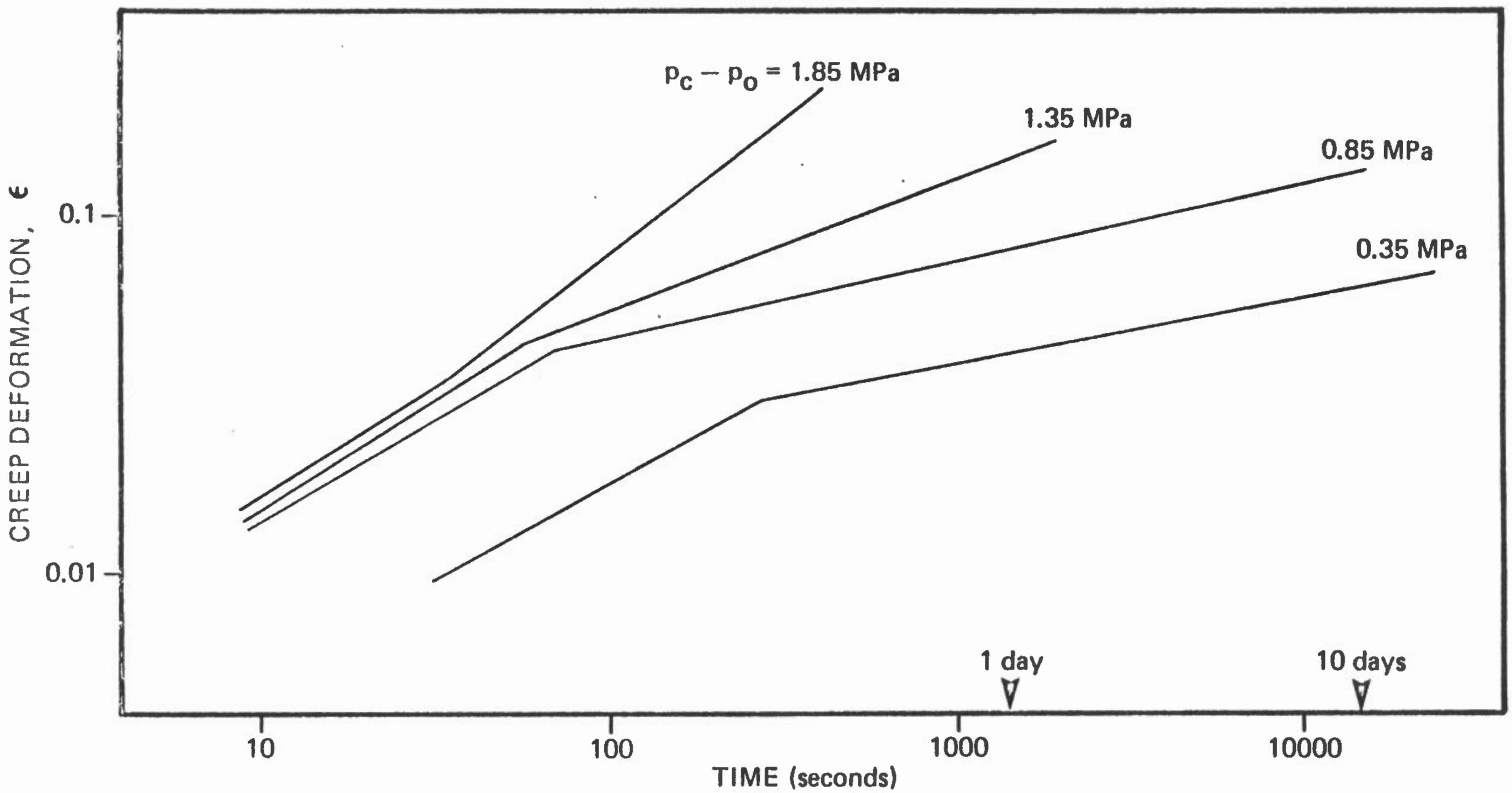

FIGURE 6.5 LONG TERM CONSTANT LOAD CREEP TESTS FOR SAND
(After Lemaire, 1983)

stresses produced within it have been determined on a continuous basis over the length of the pipe during two periods of freezing and one period of thaw.

(2) Soil total stress, ground surface displacement, ground temperature and moisture parameters have been concurrently recorded at numerous points.

(3) Laboratory studies (in Canada) have provided information on the creep properties of the soils when frozen, on the frost heaving characteristics of the soils, and on their suction-water-content relationships.

(4) In addition to the calculations required to obtain the values noted under (1), consideration has been given to the interrelation of the frost heave and creep of the frozen ground with the behaviour of the pipe. This problem, upon the solution of which the development of predictive models depends, has proved very complex. It is the main focus of current work, which also includes continuation of data collection during progressive enlargement of the frozen ground annulus.

CONCLUDING REMARKS BY PRINCIPAL INVESTIGATOR

The harmonious working relations between all involved in this project have continued during the past year. The project has now resulted in five Canadians having the substantial benefit of several months at the experimental station as field project managers. More have benefitted from short visits and from the studies being carried out in Canada.

The project has received widespread publicity in major French newspapers and, although similar publicity has not occurred in Canada, with the project becoming more known the number of well-qualified applicants to participate in the project has increased significantly. It is hoped that the specialized experience needed for the analytical stages of the project will continue to be available during the coming years. The Memorandum of Agreement provides for continuation of the experiment until December 1984, with the possibility of extension.

Interest in the project by pipeline companies and others has led to plans for a two-day seminar to be held at Caen, April 25-26, 1984. Several short publications have appeared or will appear shortly describing the project and more detailed scientific papers are now being initiated.

Although experimental data is transmitted from France to Canada by magnetic tape, the draft versions of this report, illustrated material, etc. have largely been sent by regular mail services. The exchange of material in this way has necessitated some delay in final preparation.

Finally it may be noted that there has again been no cost over run with this phase of the project, in spite of heavy inflationary pressures in France.

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2) Geotechnical Science Laboratories 1983. Investigation of Soil Freezing in Association with a Buried Chilled Pipeline in a Large-Scale Test Facility:Phase 2. Report IR-33, 41 pp.

3) Geotechnical Science Laboratories 1982. Feasibility Study for Stresses in a Pipeline Buried in Freezing Soil. Report IR-32, 36 pp.

4) Geotechnical Science Laboratories 1979. Procedure Manual for Determination of Thermal Properties of Soils. Report LTR-11, 113 pp.

5) Lemaire, G. 1983. Etude Experimentale d'un Gasoduc Enterre Soumis a des Temperatures Negatives. Memoire presente en vue de l'obtention du grade de Maitre es Science Appliquees (M.Sc.A.), 67 pp.